INFLUENCE OF THE CHELUNGPU FAULT ON A HIGHWAY BRIDGE FOUNDATIONS AND COUNTERMEASURE

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1. INTRODUCTION

The Gi-Gi earthquake on 21 September 1999 caused by the movement of the Chelungpu fault in Taiwan had made severe damages to some bridge foundations of a highway that is under construction at Nan-Tou County in central Taiwan. Because the superstructures had not been placed yet and only the piles and part of the pile caps and piers had been completed at that time, the dynamic interactions between the piles and the ground are mainly kinematic interaction with little inertia effects. An extensive pile integrity investigation by coring of the piles was conducted to investigate the damages of the piles and to judge whether the pile can still be used. This paper discusses the damages of the piles found in the investigation, the influence of the damages to the performance of the piles, and the countermeasure.

2. THE CHELUNGPU FAULT

The Chelungpu fault is a reverse fault with a strike approximately in North-South direction. The east side of the fault is the hanging wall consisting of sedimentary rocks of interbedded sandstone, shale and mudstone. The west side of the fault is the footwall consisting of mainly conglomerates and gravelly materials. The location of the Chelungpu fault at this site is shown in Figure 1. In the vicinity of this site, many minor faults were identified within a distance of approximately 400 m on the eastern side of the main fault. Vertical displacement of those minor faults can be as high as 0.3m. One of the characteristics of the Gi-Gi earthquake is that its vertical peak acceleration is very high. From the acceleration records of the Gi-Gi earthquake at the nearby strong motion monitoring station, the peak ground acceleration (PGA) in EW direction is 1g, 0.62g for NS direction, and the vertical PGA is as high as 0.34g.

3. THE BRIDGES AND DISPLACEMENT OF THE PILE FOUNDATIONS

As shown in Figure 1, in this site there are 4 routes, including the Main line and 3 ramps (Ramp1, Ramp2, and Ramp4) connecting to the rest area. The location of the Chelungpu fault had been identified by the geotechnical investigation conducted during the design stage. Therefore, in the beginning of the planning stage for this highway section, embankments were once considered; however, due to the fault was classified as a suspected active fault and there are many limitations, such as drainage system for the local area, rural roads, agricultural canals, and right of the way, the design was bound to select bridge structures for this section. Simply supported girders were chosen for the spans of the bridges crossing the fault. This is because if the bridges are once damaged in an earthquake or the fault movement, they can be easily and quickly repaired, and the cost will be relatively low. In addition, restrainers were adapted for preventing loss of span, and earthquake resistance design was made for the bridges. The pile diameter is 1.5m for the

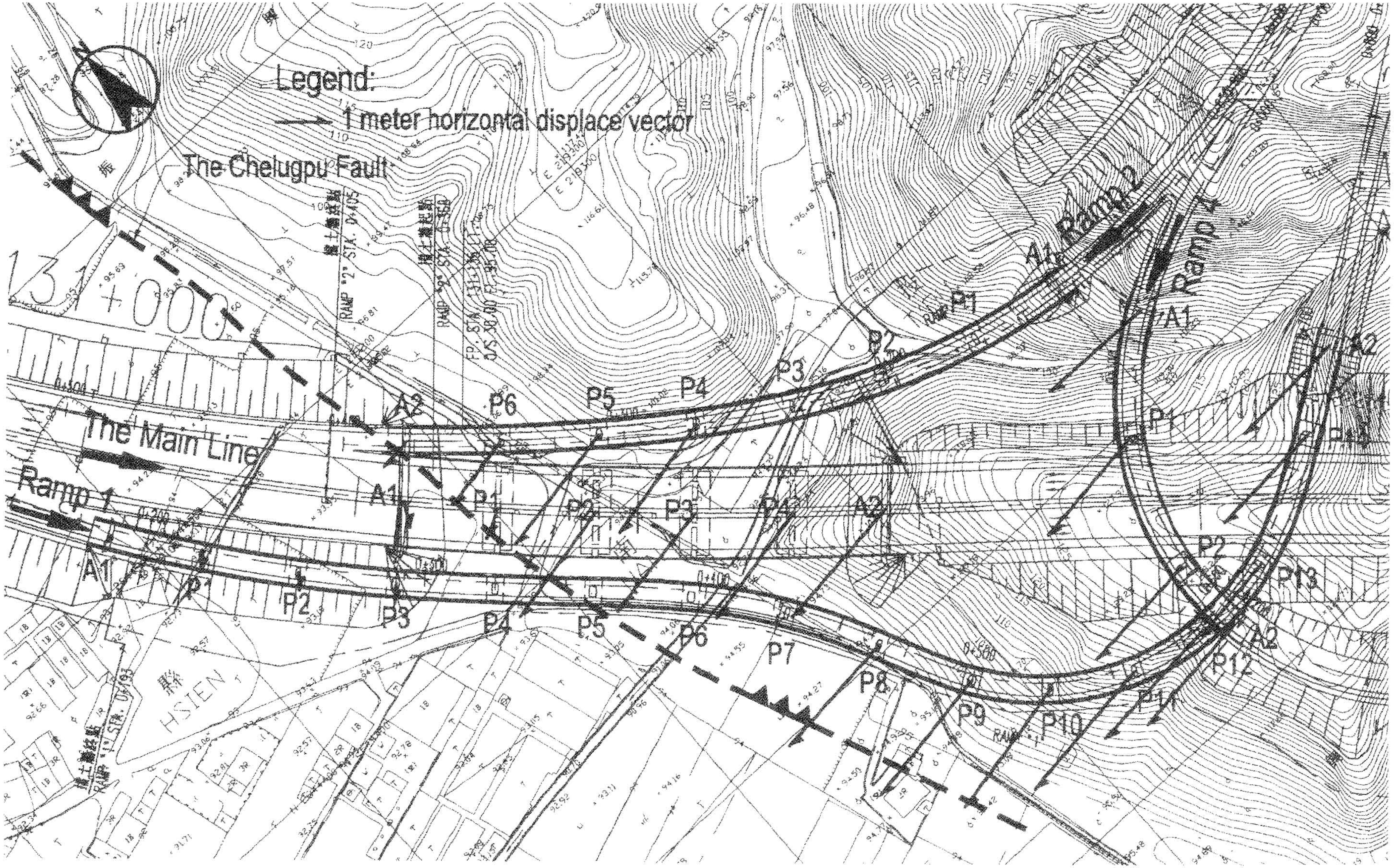

Figure 1 Layout of the 4 Routes and the Horizontal Displacement Vectors at the Piers

Main line and 1.2m for Ramp1, Ramp2, and Ramp4. The spacing of the piles is 2.5 pile diameters. The pile lengths are ranging from 9 to 30m. The piles are full cased bored piles with the requirement of verticality of 1/200.

After the earthquake, damages to the abutments and piers can be observed. For example, the Pier P5 of Ramp1 was seriously tilted by the movement of the fault. The tilting is as large as 1/11. The abutments of Main line A1 and Ramp2 A2 collided and produced many severe cracks. The ground was also displaced and uplifted in the hanging wall. From the survey of the piers after the earthquake, the horizontal displacement at Ramp1 P11 is as large as 2.71m, and the uplift displacement at Main line P4 is as high as 1.64m. The averaged horizontal displacement vectors of the pier are plotted in Figure 1.

4. THE PROGRAM OF PILE INTEGRITY INVESTIGATION

After the earthquake some of the piles were excavated for inspecting the damage condition of pile heads directly. Cracks were found near the connection of the cap and the piles at Ramp2 A2. Therefore, function of the piles was suspected and inspection of pile integrity of the site became necessary. Indirect sonic methods were not selected because caps were completed at many pile groups and the results will be hard to be analyzed if the cracks are more than two. To inspect the integrity of the piles for this site, direct coring method was used to sample the concrete from the center of the piles. For every pile sampled, the coring was continued through the pile tip for at least one meter to verify the ground condition below the pile tips and to see whether the pile tips are located in hanging wall or foot wall. The type of core barrel employed is triple tube to reduce disturbance to minimum and to get the best quality samples. The diameter of the cores is 6.4cm. In general, one pile was chosen from each pile group for coring, unless it was not accessible. There were 27 piles subjected to coring and this number is 9.3% of the completed piles of the 4 routes. A total of 547 meters of cores were sampled.

5. RESULTS OF THE INVESTIGATION

Because the drilling was positioned to start from the center of the piles, if any pile is seriously tilted, the coring will encounter the main reinforcement or hoop rebars, and may break through the side of the pile into the ground before reach pile tip. If this situation happens, a measurement of the verticality of the borehole by inclinometer and the tilting of the pile was calculated based on the depth where the borehole encounter the rebars and the verticality of the borehole. There are 11 piles found to be seriously tilted and the calculated verticalities for the piles are shown in Figures 2 to 5. The verticalities are ranged from 1/10 to 1/49. All the core samples were carefully examined for cracks. During the examination, cracks caused by man-made activities were excluded. The cracks are plotted at their locations for easy evaluation as shown in Figures 2 to 5 for the Main line, Ramp1, Ramp2 and Ramp4, respectively. Besides the crack distribution, these figures also show vertical displacements of the pile caps, and the strata just beneath the pile tips. If the stratum beneath the pile tips is rock, it can be judged that the whole pile is embedded in the rock formation of the hanging wall, and the major fault does not pass through the pile.

Figure 2 displays that the piles of the Main line were significantly fractured because the fault passes through Main line A1 and P1. Moreover, the caps of the Main line were uplifted and tilted. The cap of MP2 was uplifted 1m in average and had a 0.46m difference in level. When coring at MP2 right passed its pile tip, the advancing rate suddenly increased, the water circulation reduced and recovery of the sample was zero. An aluminous rod was used to explore the gapping phenomenon. Conclusively, a 0.8m gap was inferred at the MP2 pile.

Figure 3 shows that the crack situation in the piles of Ramp1 is severe. The fault passes through Ramp1 P5 and made it tilted. On both sides of the fault, the piles were seriously fractured. Those piles in the footwall (A1 to P5) have more cracks than those piles in the hanging wall. The possible reason is that the ground of the footwall is softer than that of the hanging wall so the pile-ground interaction was stronger in the footwall. In addition, the restraining of the caps of Ramp1 A1 to Ramp1 P3 may make more cracks near the pile heads. In addition to the cracks, gaps of at least 0.6m beneath the pile tips of R1P10, R1P14, and R1A2 were also encountered.

The fault also passes through Ramp2 A2 abutment. The cracking of R2A2 is serious. Bare eyes can easily observe tilting of R2P6. The crack distribution of Ramp2 can be seen in Figure 4. Cracks appeared to be less in the piles of Ramp4 (Figure 5) whose distance to the fault is greater than those of the other 3 routes. However, R4P1 was tilted and R4P2 has many cracks too. Moreover, a gap of 1.6m was detected beneath the pile tip of R4A2.

6. THE DAMAGE MECHANISMS AND THEIR INFLUENCES

Based on the results of the pile integrity examination and forensic investigation at this site, the possible damage mechanism and reasons can be inferred. The damage mechanisms include tilting, cracking, and pulling up of the piles.

The movement of the fault made the hanging wall displaced vertically and horizontally during the Gi-Gi earthquake. The maximum horizontal movement of the pile foundations at this site was 2.7m, and uplifting was as high as 1.6m. The ground was distorted. Also, the ground was far exceeding its elastic range during shaking and permanent plastic deformation of the ground accumulated. Many piles were therefore serious tilted.

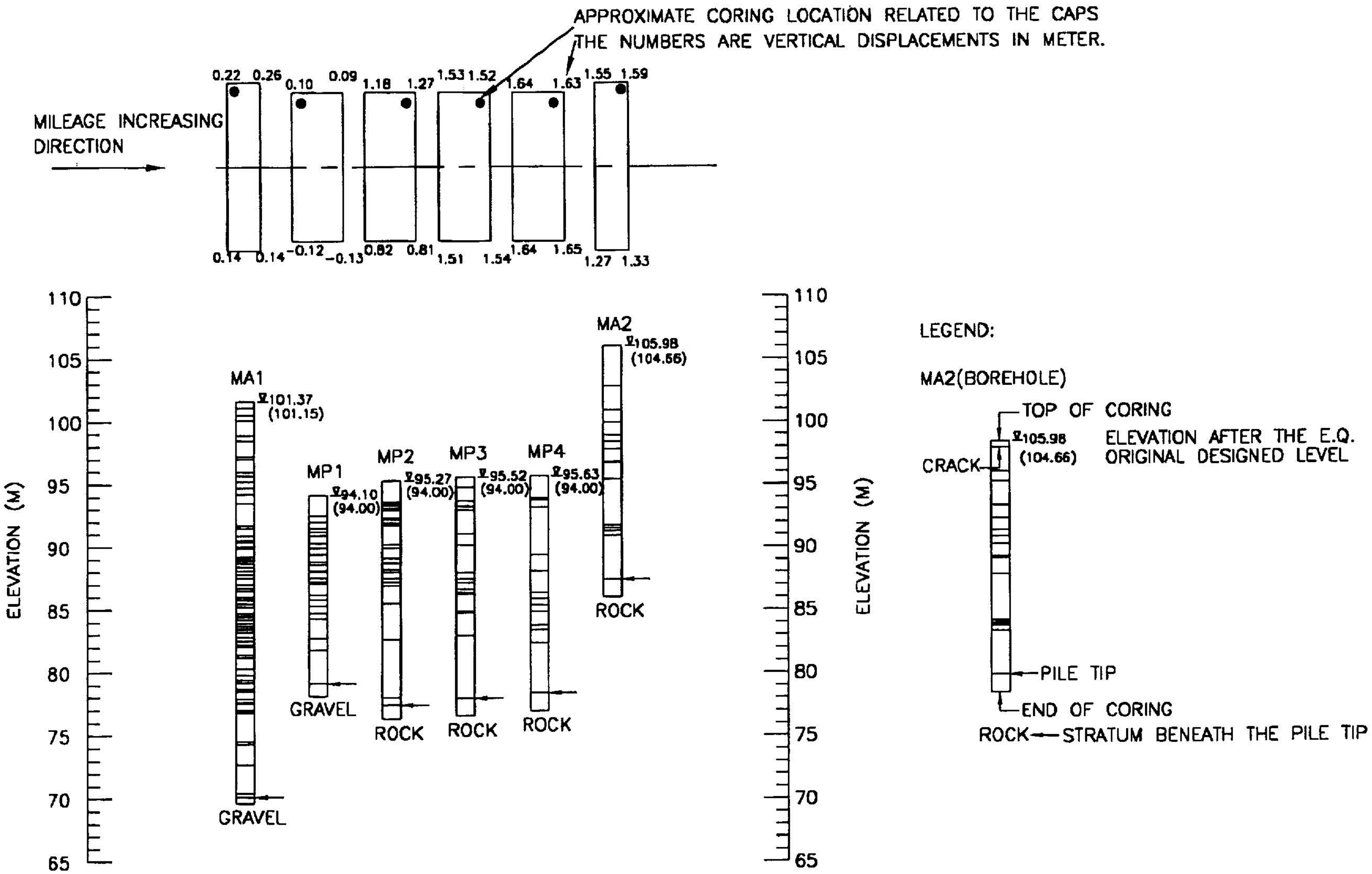

Figure 2 Crack Distribution of the Cored Piles for Main Line

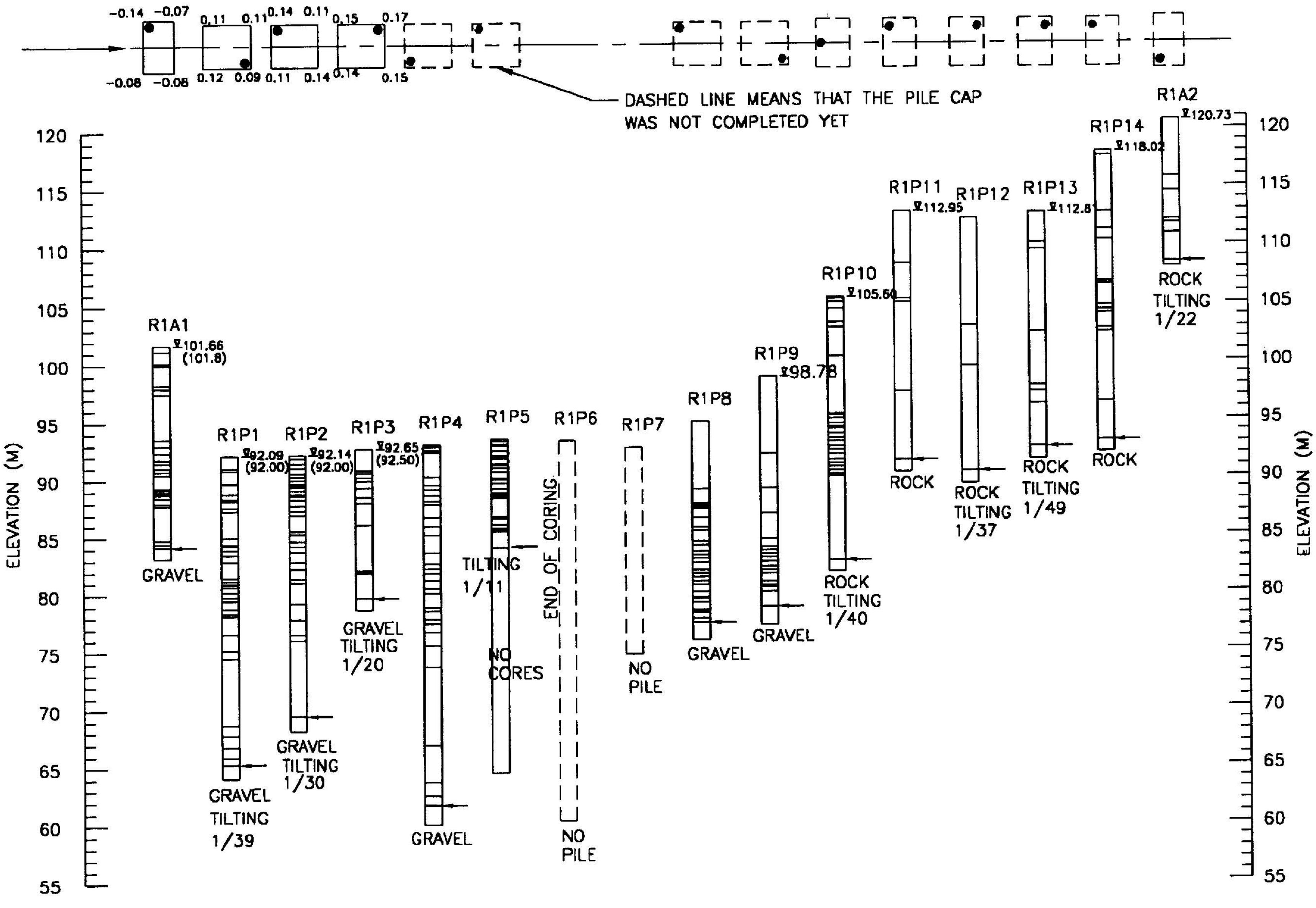

Figure 3 Crack Distribution of the Cored Piles for Ramp1

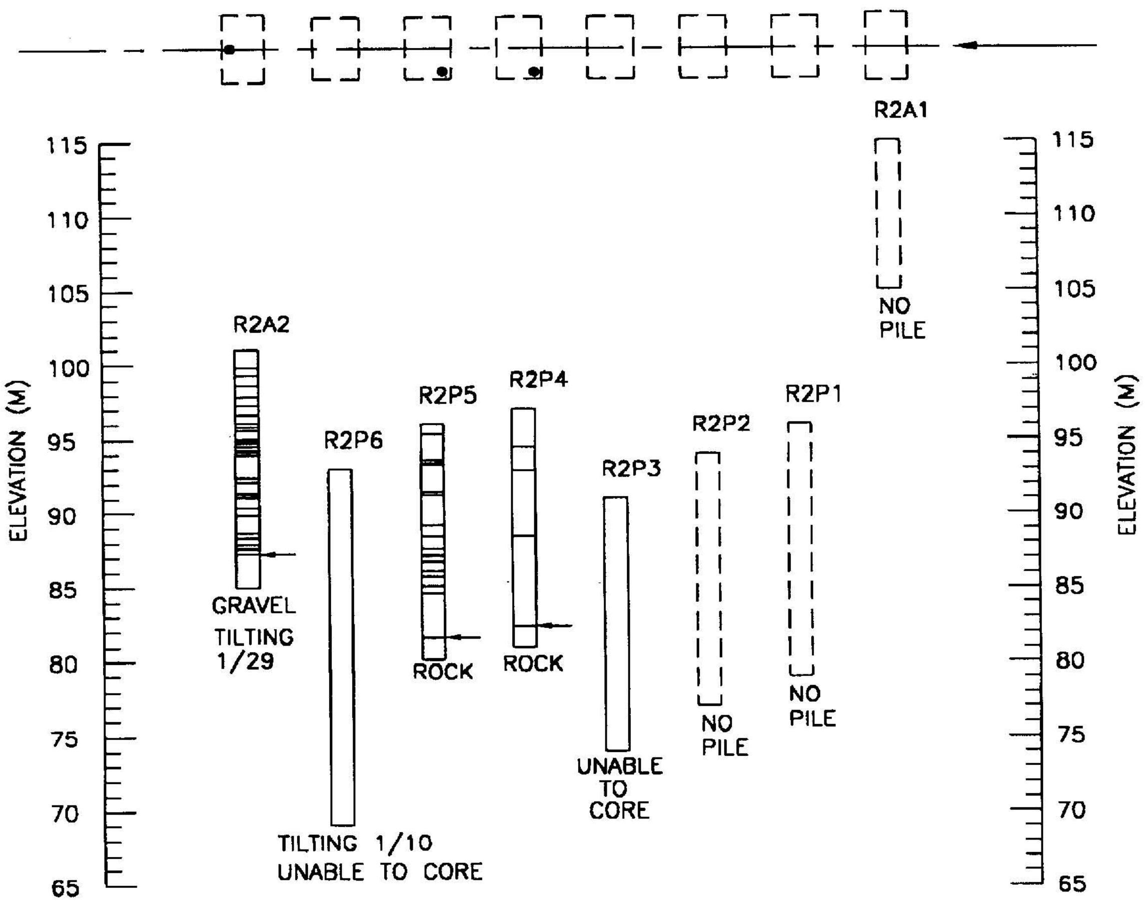

Figure 4 Crack Distribution of the Cored Piles for Ramp2

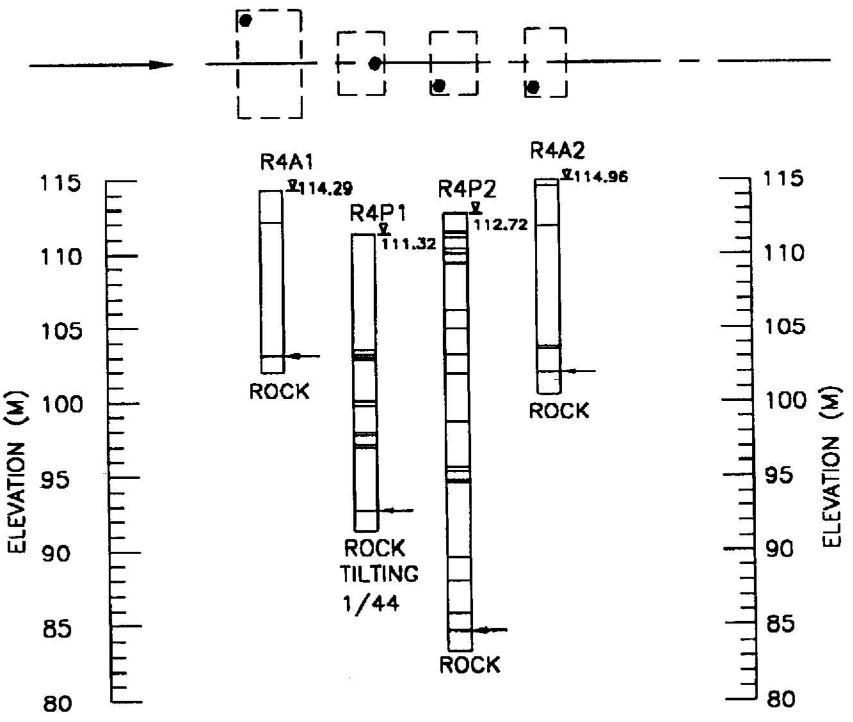

Figure 5 Crack Distribution of the Cored Piles for Ramp4

Cracks in piles developed due to that the concrete was subjected to stresses higher than their fracture strength. The stresses were mainly from the fault movement and pile-ground interaction that produced strong moment, shear, axial tension and axial compression. Moment and axial tension cause horizontal cracks in the pile; shear and axial compression may cause oblique cracks. In addition, due to the overlapping of the main reinforcements at the center of some piles, cracks are likely to appear at those overlapping locations.

The cores from Main line MP2, R1P10, R1P14, R1A2, and R4A2 showed some pulling up phenomenon. This could be due to intensive vertical vibrations, for example, 0.34g of vertical PGA as described previously, and upward movement of the fault. Therefore, the pile was very likely to be pulled up and formed a gap between the pile tip and the ground.

When pile is tilted and subjected to axial loads, it is easy to produce secondary moment. In addition, stress concentration is likely to develop at the pile tip on the bearing stratum thereby differential settlement could happen. If cracks exist in a pile, the rebars lose the protection of concrete and are subject to oxidization and corrosion, especially for those near the levels of fluctuating water table. The durability of the pile becomes skeptical. In addition, cracks reduce compressive strength of the pile due to reduction in contact area. Shear and tension capacity is reduced due to reduction in the concrete area. Also, moment resistance is significantly reduced because of reduction in the moment of inertia of the concrete section. If a pile is pulled up, only part of the residual skin friction remains and there will be no end bearing capacity. Under load, tremendous settlement might occur because of the gap between the pile tip and supporting ground.

Due to the schedule of this construction is very tight, additional coring investigation for all the piles could not be justified. In order to assure the safety of this important highway and fulfill the schedule requirement, all the piles for the four routes are prudently suggested to be abandoned and reconstructed for safety consideration.

7. THE COUNTERMEASURE

Because the same restrictions on the structure type of the original design described in Section 2 still exist, bridges are again adapted in the redesign. The alignments of the 4 routes are kept the same in the redesign. However, the piers are rearranged to keep away from its original locations to avoid the new piles encountering the previous tiled piles. In the selection of the pier locations, the piles shall avoid passing the rupture plane of the fault whenever possible. For those piers that are inevitably close to the fault, shorter but more piles are designed for the reason that more piles can still be in service if some were unfortunately cut off by future fault movement.

The PGA in this site is very high. The simply supported girders of the bridges are very likely to lose their spans due to large fault movements. In addition, the concept of easy and economical repairing is changed because human lives are deemed more valuable than the cost of repairing. Therefore, the superstructures of the bridges are redesigned by using 3 to 4 spans of continuous girders. Earthquake coefficient is raised from 0.23 to 0.33, and the latest (1995) version of highway bridge design specification by the Ministry of Transportation and Communications, ROC is strictly followed for higher standard of earthquake resistance design. Besides the restrainers at the expansion joints, shear keys are added and the support lengths of the bearing seats are increased to 1.0 to 1.2m to further prevent potential loss-of-span failure.

8. CONCLUSIONS

The movement of the Chelungpu fault accompanied the Gi-Gi earthquake of Magnitude 7.3 made a devastating damage to the central Taiwan. Some bridge foundations completed before the earthquake of a highway were suspected to be damaged. A forensic investigation was conducted to verify the usability of the piles after the earthquake. Direct coring of the piles from the center of the piles was the major method to check the pile integrity. Through the investigation, most of the piles and piers were found to be severely damaged and would have to be rebuilt. The major damage mechanisms identified are tilting, cracking, and pulling up. In the redesign of the bridges, stricter earthquake resistance considerations are made to prevent potential loss-of-span failure once the Chelungpu fault moves again.

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