# 4. DAMAGE TO TRNSPORTATION FACILITIES

## 4.1 Overview

Damage to transportation facilities, such as bridges, tunnels, earth structures in highways and railways are reported in this chapter. Damage within the affected area of the center of Taiwan Island including Chaori Prefecture, Taichung Prefecture, Nantou Prefecture, Changhua Prefecture, and Yunlin Prefecture were investigated.

Because the state highway 3rd route is running from north to south almost parallel to the Chelungpu fault which appeared on the ground. Severe damage to highway is observed on this route, especially at the bridges crossing major rivers such as Da-jia river , Wu-shi river, Mao-luoh river, and Juo-seui river. Also on State Routes 16 running in east-west direction from Mingjian to Shueili, State Route 8 from Tungshih to Yakan, and on State Route 21 running in north-south direction from Mingjian to Shueili, severe damage to tunnels, earth structures and ground failure are observed.

For railway facilities, Western mainline (mountain line) of National Railway is damaged at Dai-jia river bridge and Sanyi Tunnel. Also, local touristic lines such as, Ji-Ji line and Mt. Ali forest line are damaged.

Majority of the damage is found associated with the fault action and/or ground failure which acted as forced displacement to the structures, and several structures are damaged by strong shaking.

In this chapter, these damages are explained in detail in the order of highway bridges, highway tunnels, other highway tunnels, and railway facilities. Major interests are, investigation of the patterns of damage, and clarification of the possible scenarios, which may have caused these damages. Emergency repair actions and reconstruction measures taken at the time of mission were also studied. One of the major purpose of this mission is to cover the damage of the entire area and to preserve the undisturbed view of damage right after the earthquake before major reconstruction had taken place. Therefore, coverage of the area is emphasized rather than detailed measurements of the sites.

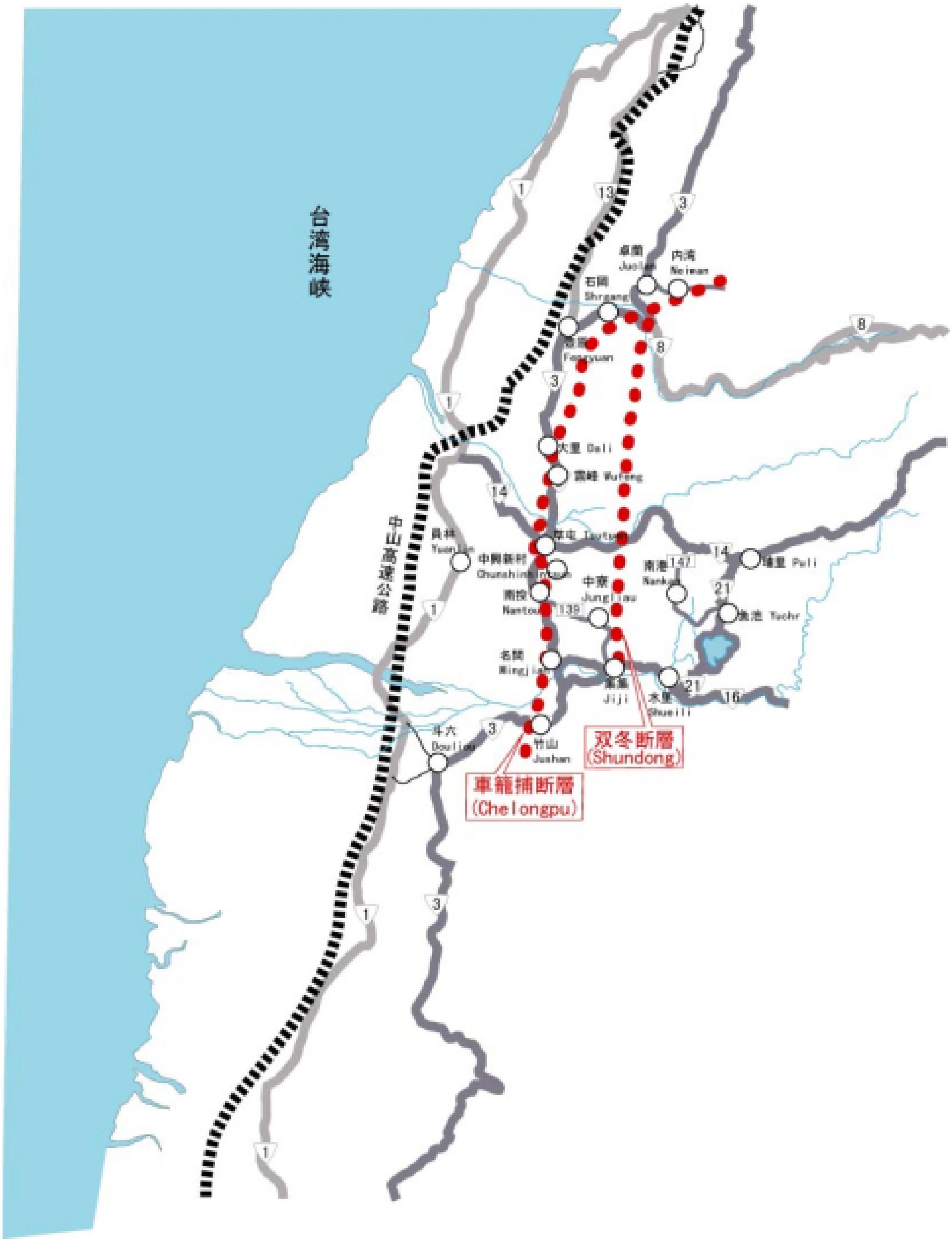



Figure. 4.1 Investigated Area

## 4.2 Highway Bridges

### 4.2.1 Overview

According to the report of Transportation Department of Taiwan Government, among 754 bridges on state highways 3,14,16,21,63,127 and 149, 10 bridges are severely damaged, and some repair works are required for 30 bridges.

In the Taichung area, there are several large rivers which are located in the east-west direction as shown in the Figure.4.1, such as Da-an river, Da-jia river (along route 8), Tou-bien-ken river, Wu-shi river (along route 14), Mao-luoh river, Juo-seui river (along route 16), and Don-puu-na river. Most of bridges in the area are on the highways and roads which cross these rivers.

Table 4.1 shows the list of the investigated damaged bridges in which the outline of the damage is included. Based on the investigation, the damage was clearly classified into two types, i.e., damage caused by the effect of fault/ground displacement, and damage caused by the strong shaking. The displacement by the fault movement is reported to be about 2 - 9 m in the vertical direction and 2 - 3 m in the horizontal direction, damage at the fault was destructive one such as falling-off of superstructures, or complete overturning of substructures. This may be the first time to have such destructive and extensive damage to bridges structures by the effect of fault displacement and also it should be noted that not only one but several major bridges were collapsed by the effect. This is discussed in 4.2.3-4.2.5.

Regarding the damage caused by the strong shaking, a bridge which was constructed in the old time was completely collapsed. Except for this bridge, the damage caused by the strong shaking seemed not to be critical. But for large structures with long natural period was affected by shaking. In the Jiji area, a concrete cable-stayed bridge under construction was not collapsed but seriously damaged at the bottom of tower, cable and deck. This also may be the first time to have such damage to large cable-stayed bridges. This failure is discussed in details in 4.2.6.

In this section, first seismic design code in Taiwan is reviewed in 4.2.2, and several major failures are discussed in detail in 4.2.3-4.2.6. In 4.2.7, damage of other bridges is briefly reviewed. Damage to secondary structures such as light poles and expansion joints which would affect the serviceability of highway is shown in 4.2.8, and emergency actions taken at the bridges at the time of investigation is reported in 4.2.9.

### 4.2.2 Seismic Design Specifications for Highway Bridges in Taiwan

Based on the Taiwanese Seismic Design Specifications for Highway Bridges issued in 1995 [Department of Transportation, National Taiwan Government : Seismic Design Specifications for Highway Bridges, Jan., 1995], the seismic design specifications were firstly issued in Jan. 1987, and in the section 2.20, most of the 1980 Japanese Seismic Design Specifications for Highway Bridges were referred in the design. Then, the Japanese Seismic Design Specifications were revised in 1990, and AASHTO issued Standard Specifications for Highway Bridges in 1992. Based on these recent development of the seismic design methods, the Taiwanese Seismic Design Specifications have also been revised in 1995.

The design specifications are basically applied to the bridge with span length equal to or less than 150m. Two level design method is employed, i.e., against small earthquakes the bridges should be in the elastic range, and against large earthquake the bridge should behave in ductile manner without collapse. It is noted that the importance of the ductility is emphasized and the ductility design methods for reinforced concrete columns are specified.

In the static design method, the following lateral design seismic force is specified. This is the minimum design seismic force.

$$V = \frac{ZI}{1.2\ \alpha_y} \quad (C/Fu)m\ W \qquad (4.1)$$

In which,

V : Lateral seismic force

Z : Design acceleration

I : Importance factor

$\alpha y$ :Yield seismic force factor

(C/Fu)m: Modified response factor of acceleration

W : Weight

Design acceleration, Z, employs a specified value as 0.33, 0.28, 0.23, or 0.18 depending on the regional earthquake characteristics as shown in Figure. 4.2. These values were determined based on the risk analysis with consideration of return period of 475 years. It should be noted here that the affected area of this earthquake is categorized in the 2nd and 3rd category, where the corresponding design seismic acceleration on the ground surface is 0.28 or 0.23.

Importance factor is taken as 1.2 or 1.0 depending on the importance of the highway. Yield seismic force factor, $\alpha y$, is 1.7 for steel bridge, 1.65- 1.90 for reinforced concrete bridges. Modified response factor of acceleration, (C/Fu)m, is defined as

$$C/Fu \leqq \begin{cases} 1.2\ (R^*=2.0) \\ 1.1\ (R^*=3.0) \\ 1.0\ (R^*=5.0) \end{cases} \qquad (4.2)$$

in which,

R* : Modification factor for structural characteristics, 2 for wall type column, 3 for single column, 5 for multi column bent

Therefore, suppose the area with high earthquake risk (0.33), high importance highway, and reinforced concrete single column, the lateral seismic forces is calculated as

$$V = \frac{0.33 \cdot 1.2}{1.2 \cdot 1.65} \quad 1.1W = 0.22W \qquad (4.3)$$

Right after this earthquake based on site investigation of the bridges in the region, Bridge Engineering Center at Taiwan Central University has issued the following recommendations:

1. Investigate details on seismic risk and effect of fault when selecting the location of bridges.
2. Re-evaluate seismic area and design spectra.
3. Evaluate of seismic excitation near fault and include it into the seismic design code of bridges.
4. Accelerate the inspection and seismic retrofit of transportation department, and enhance the seismic performance of bridges.
5. Construct alternate highway networks, to establish emergency rescue network at the time of failure of bridges.
6. Strengthen the capacity of inspection and maintenance of authorities of city and county level.
7. Equally weight the new construction and maintenance to constantly finance the maintenance works.
8. Standardize the maintenance and inspection method of the entire state.

The effect of fault, network performance of highways, and seismic retrofit and maintenance are emphasized to improve seismic performance of these structures.

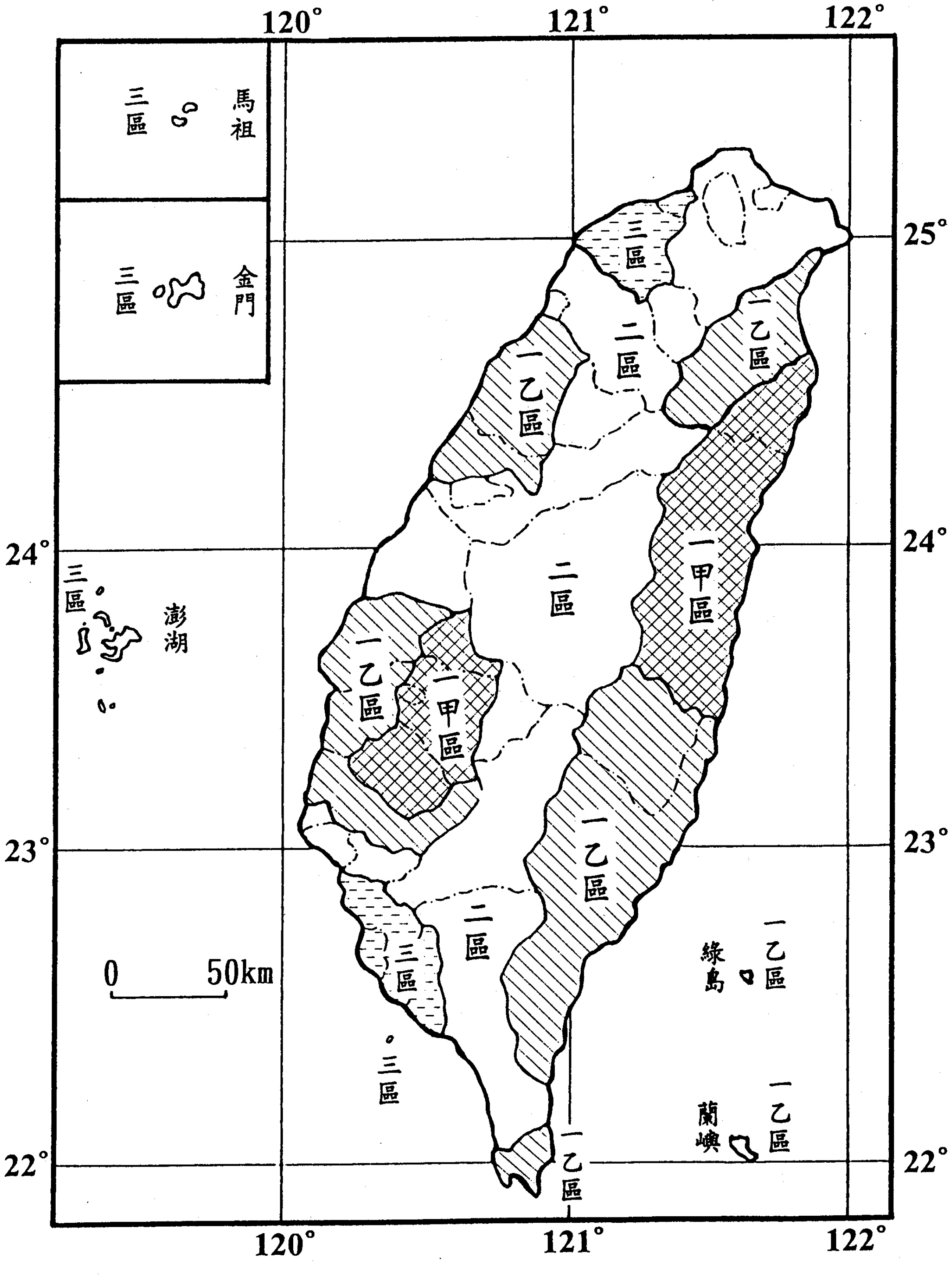



圖2.1 台灣地區震區劃分圖

Figure. 4.2 Regional Category on the Earthquake Risk

### 4.2.3 WU-SHI Bridge

As shown in Figure. 4.3 and Photo 4.1 and 4.2, two girders towards the end of the bridge on the upstream side, namely girders between abutment A1 and pier A3 fell from the piers and a pavement around the abutment was lifted up by about 50 cm. Damage appeared to be caused by pounding observed at the end of the girder at pier A3. The road surface was subsided by approximately 70 cm at this location. This subsidence seemed to be too large compared with the behavior of the girders which fell from the bridge seats by 40 cm. It might also be affected by the vertical displacement of the piers and ground.

The damage to the upstream side of the bridge was probably caused by the following process:
(1)Girders were pushed forward to the north direction of the bridge axis due to large horizontal forces or the movement of the ground.
(2)The girder at the end of the bridge clashed against the abutment, resulting in the bulging of the paved road surface.
(3)The girder at the end of the bridge on the north side（between abutment A1 and pier A2）moved by approximately 50 cm. This length exceeded the length of the bridge seat and ended in the fall of the girder.
(4)Similarly, the girder between pier A2 and A3 suffered large movement, especially on the pier A3 side, eventually causing the girder to fall.

Regarding the damage on the downstream side of the bridge, the wall type piers B2 and B3 sustained serious damage in the bridge axis direction, with cracks penetrating through the piers. Pier B4 indicated no serious damage, but it tilted to the downstream side by approximately 5～7 degrees and its road surface subsided by about 70 cm. On piers B5 and B6, horizontal cracks of flexural type were observed at the mid-height. This portion is presumed to be the joint of the concrete.

The damage on the downstream side was probably caused by the following process:
(a)Flexural and shear damage occurred on the piers due to large seismic forces or the movement of the ground. Although pier B3 and B4 seemed to be moved by 1 to 2 m in the direction perpendicular to the bridge axis, and girders on them didn’t move to that direction. However, it is very unlikely that piers supporting simple girders, or unconfined piers fail by shear only by the movement of the ground. Therefore, to solve this contradiction, a detailed measurement of the movement of piers and girders is needed.

(b)According to the results of the Schmidt hammer test on those piers, the concrete strength exceeding 290 $kgf/cm^2$ was obtained. Therefore, it can be said that those piers are sound in quality, though the main reinforcement ratio is relatively small because they are of the wall type.

Damage to this bridge is summarized as follows:
(i)The damage patterns of piers and girders differ between those on the upstream side and those on the downstream side.
(ii)On the upstream side, damage was caused by the crashing of the girder to the abutment which resulted in the falling of the girder.
(iii)On the downstream side, shear failure was caused on the piers in the direction perpendicular to the bridge axis even though resistance of wall-type pier is greater in that direction.

### 4.2.4 MING-JUU bridge

The bridge is a four-girder simply supported bridge with a span length of about 23 m each. Regarding piers A3 and B3 and four girders existed between piers A2 and A4 and piers B2 and B4, a detail investigation was not feasible because they had already been dismantled. Therefore, press photos taken earlier were used instead for assessing the damage to those piers and girders. On the upstream side, pier A3 tilted significantly to the south direction and the girder between pier A3 and A4 fell down, as depicted in Figure. 4.4. On the downstream side, pier B4 suffered shear damage (Photo 4.3), pier B3 tilted seriously to the south direction, and girders between pier B2 and B5 were seen virtually to have fallen.

The damage to the upstream side was probably due to the following reasons:
(1)Pier A3 hideously tilted to the south direction due to strong seismic forces, causing the girder between pier A3 and A4 to fall. Or, the girder might have fallen off due to the elongation of the span length between piers A3 and A4 induced by large displacement that occurred in the horizontal direction.

The process which caused damage to the downstream side was probably as follows:
(1)Shear damage which occurred on pier B4 at its upper portion might have caused the falling of girders existed between piers B3 and B4 and piers B4 and B5.
As to a girder between piers B2 and B3, it probably fell from pier B3 before the pier underwent tilting because the pier seems to lean over the girder. It is considered that after the girder between piers B2 and B3 fell due to large horizontal displacement,

horizontal forces generated by the falling of the girder between piers B3 and B4 were imposed on pier B3 to make it tilt.
The strength of pier B4 obtained by the Schmidt hammer test was 260 $kgf/cm^2$ and the surface condition appeared to be sound, indicating that no problems existed in terms of quality.

Damage to this bridge is summarized as follows:
(1)Horizontal displacement to the level causing girders to fall occurred between piers A2 and A4 on the upstream side and between piers B2 and B4 on the downstream side.
(2)Pier B4 showed shear damage at its upper portion where main reinforcement was probably partially terminated.

**4.2.5 CHANG-GENG Bridge**

Figure.4.5 and Photo 4.4 show the damage situation of this bridge. As seen, piers indicated no obvious damage, but girders between piers A1 and A2 and piers A2 and A3 on the left bank side fell off the piers. The bridge is a five-girder PC bridge with a width of 13 m and a span length of 30 m each. The entire span length is approximately 400 m. The bridge seat to support the girder is only about 50 cm long.

The process behind the damage was probably as follows:
(1)Large horizontal forces or the shift displacement of the ground occurred in the direction from right bank to left bank（from north to south）.
(2)Girders on the right bank side were pushed out of the alignment in a phenomenon like a pileup car accident.
(3)It was found that girder A4 moved by 50 cm and girder A3 by 70 cm (Photo 5). Also, no expansion spacing was found between girders. From this observation, it can be said that horizontal forces or displacement of the ground which caused significant movement of the girders were dominant in the direction from north to south.

The characteristics of the damage to this bridge are summarized as follows:
(i)The primary causes of the falling of the girders are presumed to be the movement of girders in a phenomenon like cars bumped in a pileup accident and the lack of the length of the bridge seat. Further investigations are needed to obtain the relationship between the amount of movement of the pier and the direction of fault movement.

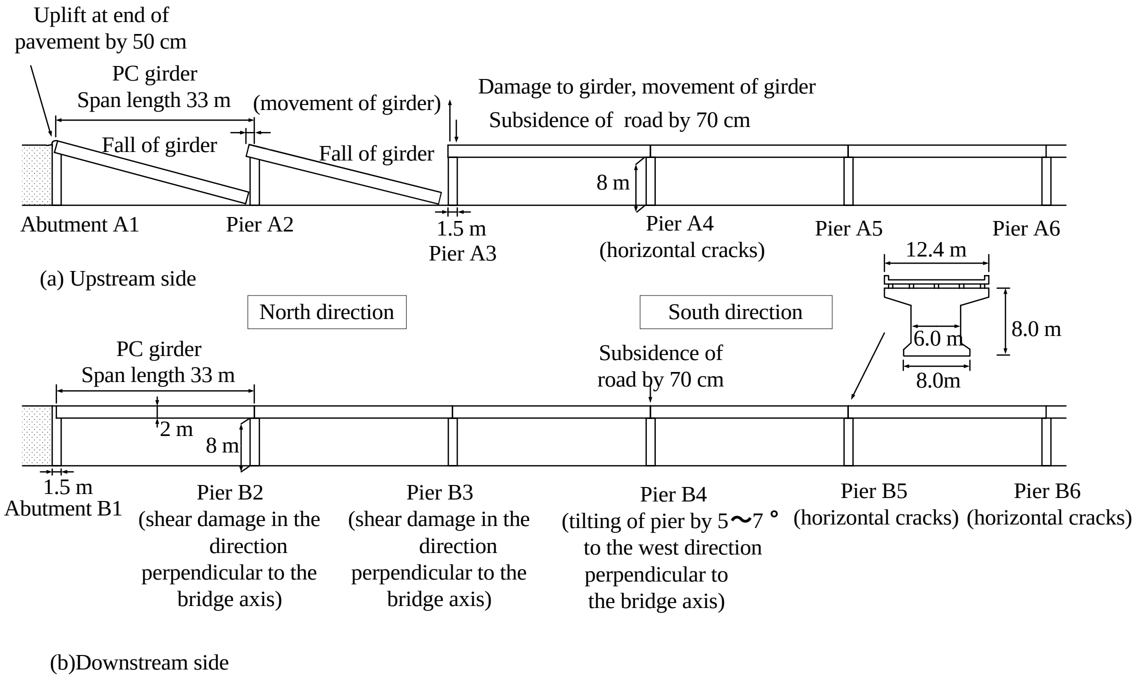



Figure. 4.3 Damage to WU-SHI Bridge

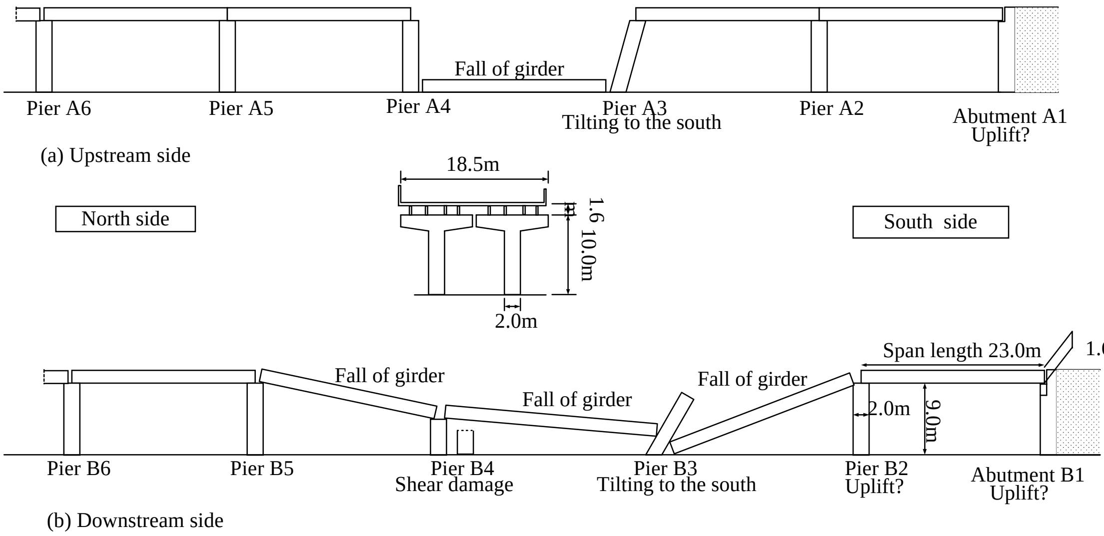



Figure. 4.4 Damage to MING-ZHU Bridge

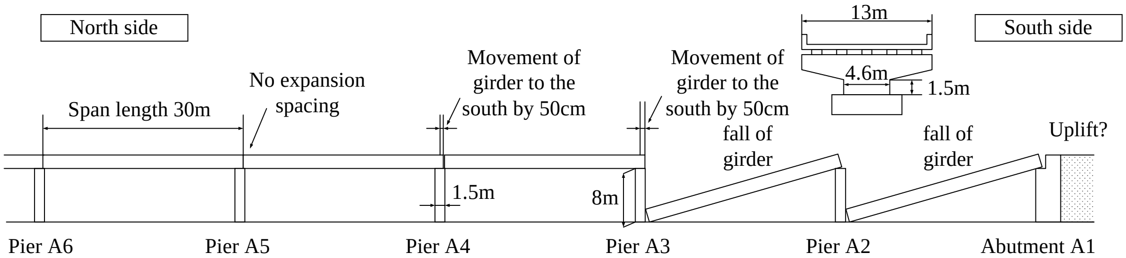



Figure. 4.5 Damage to CHANG-GENG Bridge

Photo 4.1 Failure pattern of WU-SHI Bridge

Photo 4.2 Shear failure of the wall-type pier

Photo 4.3 Failure of the Pier B4 of MINGZHU Bridge

Photo 4.4 Failure pattern of CHANGGENG BIG Bridge

### 4.2.6 Ji -Ji Da Bridge

Photo 4.5 Overview of Ji-Ji Da Bridges

This bridge is located in the south in Ji-Ji Village, and crosses over Juo-Suei-Shi River. This bridge is under construction. It consists of one cable stayed bridge (Photo 4.5) of 4 traffic-lanes, two 8 span prestressed concrete simple-girder bridges and 3 span continuous rigid-frame bridge (Figure. 4.6).

The span length of the cable stayed bridge is about 110 m. The height of a main tower is about 50 m, and its cross section at the bottom is 6 m x 2.5 m. The main girder is made by precast blocks, and connects with the main tower rigidly. The both end of the girder are supported by rigid-frame piers. There are two planes of cables, and rubber gaskets have been installed at both ends.

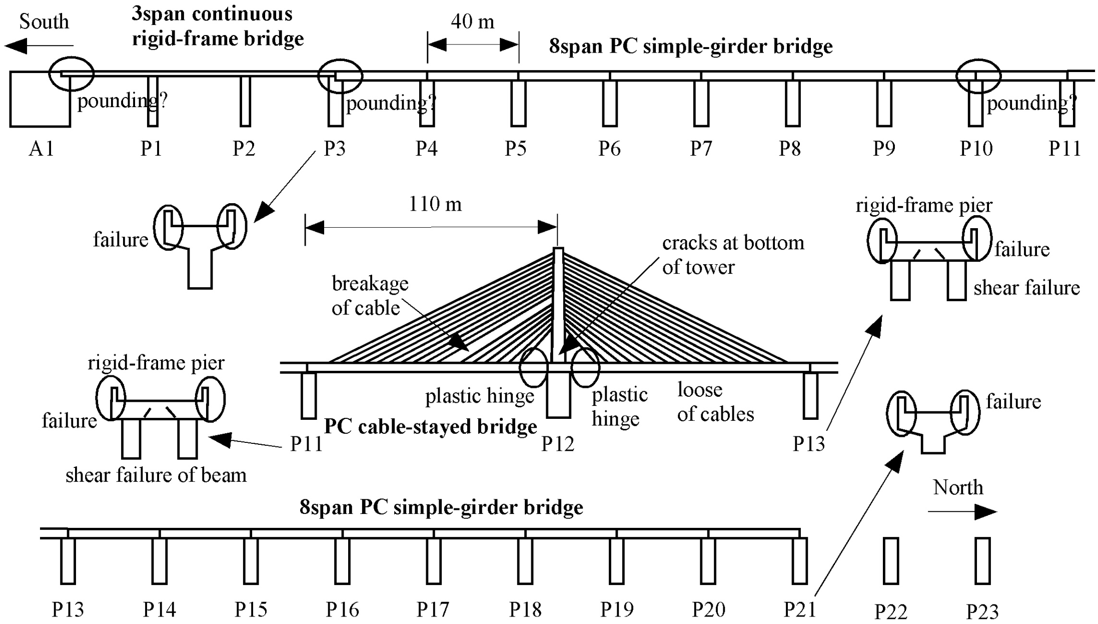



Figure 4.6 Overview of Ji Ji Da Bridges

### (a) Damage of the Cable Stayed Bridge

The main tower received flexural and torsional cracks. The cover concrete has been spalled and the hoop has been exposed at the bottom (Photo 4.6, Figure. 4.7). The hoops are the U-shaped type and the pitch is about 10 cm. The core concrete appear to sustain no severe damage.

One cable in the south side east plane failed. At the connection between cable and girder, the coupler, made of the cast iron, broke and the cable escaped (Photo 4.7).

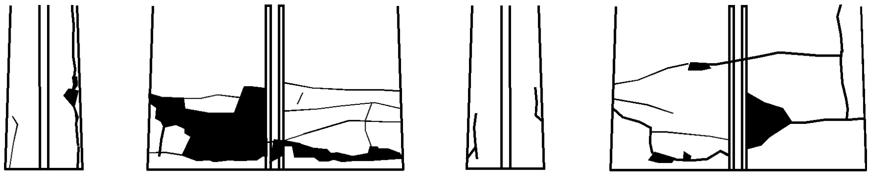



Figure 4.7 Crack Patterns of Main Tower

Photo 4.6 Cracks of Main Tower

Photo 4.7 Breakage of Cable (Damage Rank As)

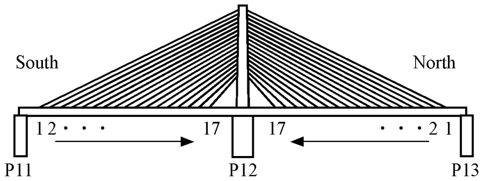
Photo 4.8 Pull Out of Cables (Damage Rank A)

Also, cable mounting couplers of other cables have pulled out from the girder (Photo 4.8). The detail investigation of the cable damage is shown in Figure. 4.8. Damage rank As shows the breakage, A shows severe damage (pull out of rubber gasket), B shows medium damage (pull out of coupler), C shows slight damage (crack of coupler) and D shows miner or no damage. As these data suggest, many cables seem to be loosened, and it is possible that the variation of cable tension occurs.

At the girder near the main tower, severe damage due to reinforcement buckling was observed (Photo 4.9). It is supposed that the girder vibrated due to the earthquake and at the fixed point, the connection between the tower and the girder, the damage had occurred by excessive moment and crushed by the compression force induced by the cables.

The rigid-frame piers at the end of the girder suffered severe damage. Shear crack penetrated the upper beam, and the shoes were broken (Photo 4.10). And the wall parapets were also broken because the girder moved laterally about 50 cm.

According to the information of Prof. J.C. Chern of National Taiwan University, the construction company just took away the tower crane, which located at the empty hole near the




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| South-East | D | D | A | A | D | A | D | D | D | B | As | D | D | D | D | D | B |
| South-West | A | D | D | A | D | D | D | D | D | D | D | D | D | D | A | D | A |
| North-East | D | C | A | D | A | A | D | D | D | A | D | D | D | D | D | A | D |
| North-West | D | D | A | D | A | D | D | D | A | A | B | D | D | D | D | D | D |

Figure 4.8 Damage Rank of Cables

Photo 4.9 Buckling of Reinforcement

Photo 4.10 Shear Failure of Rigid-Frame Pier

tower. This may be the major reason why it vibrated so much during the great earthquake.

### (b) Damage of Other Bridges

In the adjacent 8 span simply supported girder bridge, many ends of girders were broken by pounding (Photo 4.11). Some girders also moved about 20 cm in the transverse direction. And the wall parapets of pier P3 were broken (Photo 4.12). But for the T-shaped single column piers underneath seem to be no damage.

Photo 4.11 Pounding Failure of Girder

Photo 4.12 Failure of Wall Parapets

#### 4.2.7. Damage to Other Bridges

**(a) SHI-WEI Bridge (Photos 4.13, 14)**

Simply supported concrete girder bridge, which consists of structurally independent two neighboring bridges. Both bridges collapsed. Ground failure is observed at the adjacent bank and piers incline considerably. The main cause of this damage is the ground displacement due to landslide or fault. Development of shear cracks are observed at the bottom of piers.

Photo 4.13 Overview of Shi-Yuen Bridge

Photo 4.14 Damage of the pier

**(b) DONG-FON Bridge (Photos 4.15-17)**

Photo 4.15 Dong-Fon bridge overview

Photo 4.16 Damage at girder edge

Photo 4.17 Road surface

In simply supported concrete girder bridger, shear failure, and failure at the middle were observed at a group of three piers. All the damaged piers were damaged in transverse direction. Also, damage at girder edges (Photo 4.16) due to failure of bearing and/or pounding is observed.

The bridge consists of three parts in transverse direction, i.e., central part, which is the original construction, and adjacent two parts which are the new extention of traffic lanes. Therefore, the bridge is made of three structurally independent parts in transverse direction, which are connected only at the slabs. Longitudinal crack on the lane (Photo 4.17) which is appeared to be caused by failure of bearings, three lanes were closed.

**(c) BEI-FON Bridge (Photos 4.18,19)**

Photo 4.18 Bei-Fon Bridge

Photo 4.19 Collapsed substructure

Simply supported concrete girder bridge. Fault run directly underneath the bridge, which is the major cause of this collapse.

**(d) II-JIANG Bridge (Photos 4.20-22)**

Photo 4.20 Ii-Jian Bridge

Photo 4.21 Shortened span

Photo 4.22 Ii-Jian Bridge
(Courtesy of Prof. M. Yoshimine, Tokyo Metropolitan University )

Simply supported concrete girder bridge. Several spans fell off consecutively. The cause of this failure is shortening of a span by approximately 4m as shown in the photo. Other spans received relatively minor damage. Evidence of ground failure which appears to be related to fault action is observed around the region.

**(e) EN FON Bridge (Photos 4.23-25)**

Photo 4.23 En-Fon Bridge substructure

Photo 4.24 Beam-Column Connection

Photo 4.25 Bearing and side stopper

Simply supported concrete girder bridge mounted on rigid frame type pier. One lane was closed due to expansion joint failure. The other lane also received damage at the expansion joint and had a step of 5cm, which forced the traffic to slow down. These expansion joint failure appeared to be caused by the failure at the bearings.

The pier failed at the connection of the vertical column and beam. The beam slides on the column and reinforcing bars received excessive deformation and rupture. All the beams slide to the transverse direction, to the north-east. The bearings are restrained by concrete block in the transverse direction, which supposed to have higher strength than the beam-column connection and caused this damage.

**(f) PIN-LIN Bridge (Photos 4.26,27)**

Photo 4.26 Pin-Lin Bridge

Photo 4.27 Pin-Lin Bridge

Simply supported concrete girder bridge adjacent to the En-Fon Bridge. Complete collapse of the bridge is observed which is caused by the failure of reinforced concrete columns.

### (g) MAO-LUOH-SHI Bridge (Photos 4.28,29)


Photo 4.28 Mao-Luoh-Shi Bridge


Photo 4.29 Connection detail

The bridge is part of the bypass route of the State Route 3. Piers supporting the straight part of upper structure were not damaged. The piers have an elliptic cross section and are placed at the center of the width of upper structure. Some diagonal cracks were observed in piers at the junction where the highway branches out into two traffic lanes. Each branch is supported by circular sectioned piers. The piers at the beginning of branch are placed eccentrically to the width of the branch. After the earthquake, steel frames are erected as temporary additional supports of the branch.

### (h) LYU-MEI Bridge (Photos 4.30,31)


Photo 4.30 Lyu-Mei Bridge


Photo 4.31 Failure of bearing

Steel arch bridge adjacent to Juin-Gong Bridge. Evidence of liquifaction is observed around this region. Damage to bearings associated with displacement of deck is observed (Photo 4.31). Failure of abutment similar to Juin-Gong Bridge is observed.

### (i) JUIN-GONG Bridge (Photos 4.32,33)

Simply supported concrete girder bridge adjacent to Lyu-Mei Bridge. Clear evidence of liquifaction was observed. This would be the cause of the lateral settlement of the abutment along with the retaining wall to the river, which caused the failure of the abutment.

Photo 4.32 Abutment of Juin-Gong Bridge

Photo 4.33 Trace of liquifaction

**(j) YON-SING Bridge (Photos 4.34,35)**

Photo 4.34 Yon-Sing Bridge

Photo 4.35 Damage of pier

Simply supported concrete girder bridge. Serious damage to reinforced concrete columns are observed. Lateral gap between adjacent girders and damage to abutment are also observed.

**(k) YEN-PIN Bridge (Photos 4.36,37)**

Photo 4.36 Yen-Pin Bridge

Photo 4.37 Abutment

Simply supported concrete girder bridge mounted on wall-type piers. One lane was closed at the time of investigation due to failure of abutment caused by ground failure. Vertical through crack is observed at the center of the wall type pier.

### (l) LIN-WEI Bridge

Photo 4.38 Lin-Wei Bridge

Photo 4.39 Abutment

Lin-Wei Bridge, which is a steel through type arch bridge with span length of about 60m under construction, is damaged at the abutment and bearing. All of the four bearings are failed, and the bridge is moved by 40cm to the east. Both end abutments are crushed by excessive motion of the girder and pounding.

### (m) TONG-TOU Bridge (Photos 4.40,41)

Photo 4.40 Overview

Photo 4.41 Collapse of Abutment

This bridge is located in Route 149 in the south in Jushan Village. It is a 4 span RC simple-girder bridge of 2 traffic-lanes. The span lengh is about 10 m and the width is about 7 m.

This bridge was completely collapsed (Photo 4.40). Two piers are failed in shear mode and one pier fall in the ground. All decks also fall in the ground. And the abutment suffered severe damage (Photo 4.41). Beside the abutment, a large-scale collapse of rock wall was observed. It is supposed that active faults exist around the bridge, because the piers, especially the abutment, were damaged severely.

### 4.2.8 Secondary Structures

At the undamaged portion of bridges, several damages on secondary structures which affects the serviceability of highway are also observed. Photo 4.42 shows the highway on the Shi-Kan Dam. One of the lighting pole is overturned due to the failure of the anchor(photo 4.43).

Photo 4.42 Highway on Shi-kan Dam

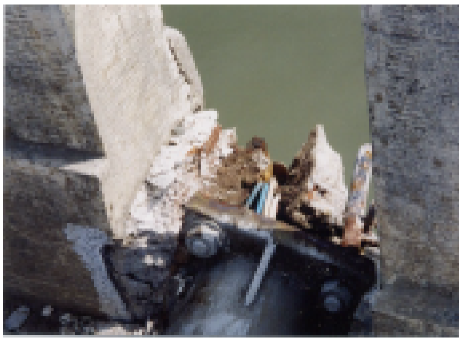


Photo 4.43 Anchor of light pole

Photo 4.44 shows the compression failure of expansion joints at Chang-Geng Bridge, and photo 4.45 shows the stretching at Ming-Juu Bridge. Both appear to be due to the excessive ground displacement at the crossing of the fault. This kind of failure at expansion joints is also observed at other bridges such as Dong-Fon Bridge and En-Fon Bridge, which resulted in closure of several traffic lanes.

Photo 4.44 Compression of expansion joint

Photo 4.45 Gap at expansion joint

### 4.2.9 Emergency Repair Action

Various measures of emergency reconstruction were taken to resume transportation at the time of investigation. Photo 4.46 shows the repair of bearing at Dong-Fon Bridge to level the road surface of the closed lane. Photo 4.47 shows the Chang-Geng Bridge right after the earthquake. Because alternate bridge is not available nearby, local residents hooked ladder at the fallen girders to pass through this bridge. Because Chang-Geng Bridge was damaged only around the attachment 2 spans to the right bank, the damaged portion was temporarily replaced by steel support and steel plate to resume pedestrian and lightweight traffic (Photo 4.48). Similar action was also taken at Ming-

Juu Bridge, where the damaged portion was replaced by soil retained by cargo containers. Photo 4.50 shows the temporary crossing at Shi-Wei Bridge. Entire Bridge is replaced by earth construction. In this way, the traffic condition was quickly resumed in this region and no major traffic difficulty was encountered during this investigation mission.

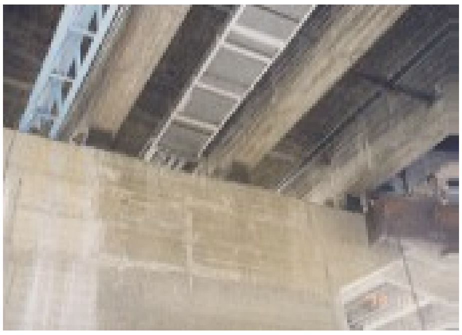


Photo 4.46 Repair of bearing at Dong-Fon Bridge

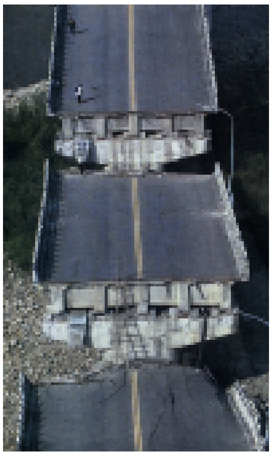


Photo 4.47 Temporary crossing at Chang-Geng Bridge

Photo 4.48 Emergent repair at Chang-Geng Bridge

Photo 4.49 Ming-Juu Bridge Repair

Photo 4.50 Crossing at Shi-Wei Bridge

**Table 4.1** List of the Damage Bridges

| River | Route | Name of Bridge | Structural Property | Outline of Damage |
|---|---|---|---|---|
| Da-an | Chung-san Highway | under construction | Simply-supported concrere girder | Slight bending-shear crack at the mid-height of the column |
| Da-jia | State Route 3 | SHI-WEI Bridge (1994.9) | 3-span simply-supported concrete girder, two adjacent bridges | Collapse of 3 girders and inclination of the columns (fault displacement) |
| | State Route 3 | DONG-FON Bridge | Simply-supported concrete girder | Damage to RC columns, vertical gap on the road surface |
| | — | CHANG-GENG Bridge | Simply-supported concrete girder | Collapse of two spans (fault displacement) |
| | — | FON-SHI Bridge | 4-span simply-supported concrete girder | Inclination of substructures, lateral gap between two adjacent girders |
| | — | BEI-FON Bridge (1991.1) | Simply-supported concrete girder | Collapse of 3 spans (fault displacement ) |
| Tou-Bien-ken | Prefectural Route 136 | II-JIANG Bridge | Simply-supported concrete girder | Collapse of 7 spans (fault displacement) |
| | — | The Water Pipe At Side Of II-JIANG Bridge | Continuos Steel Pipe with Joints | Collapse of Pipes |
| Wu-shi | State Route 3 | WU-SHI Bridge (1983.7) | Simply-supported concrete girder, two adjacent bridges | Collapse of two spans (one bridge), damage to RC columns and foundation (fault displacement) |
| | State Route 14 | EN-FON Bridge (1984.1) | Simply-supported concrete girder | Lateral gap between adjacent girders, lateral displacement of capbeam of rigid frame column |
| | — | PING-LIN Bridge (1969.1) | Simply-supported concrete girder | Complete collapse of most of girders by collapse of RC columns |
| Mao-luoh | State Route 3 | MAO-LUOH-SHI Bridge | Steel girder | Inclination of deck at the eccentrically connected columns, damage to the top of RC columns |
| | State Route 14 | LYU-MEI Bridge (1998) | Steel arch bridge | Damage to bearing, lateral displacement of deck, some liquefaction |
| | State Route 14 | JUIN-GONG Bridge | 8-spans simply-supported concrete girder | Slight damage to bearing and abutment |
| Juo-Suei-shi | State Route 3 | MING-JUU Bridge | Simply-supported concrete girder, two adjacent bridges | Collapse of 7 spans? |
| | — | YON-SING Bridge | 9 span Simply-supported concrete girder | Serious damage to columns, lateral gap between two adjacent girders, damage to abutment |
| | Central 2nd Expressway | JI-JI-DA Bridge under construction | Concrete Cable-stayed bridge | Damage to the bottom of tower, deck and rigid frame column |
| Don-Puu-na | State Route 3 | YEN-PIN Bridge (1986.2) | 6 span simply-supported concrete girder | Damage of connecting embankment (fault) |
| | | TONG-TOU Bridge | | |
| | | LIN-WEI Bridge | | |
| | | LON-CHUEN Bridge | | |
| — | State Route 16 | JiJi area | 3 span concrete frame bridge | Slight damage at the bearing |
| — | Prefectural Route 149 | TONG-TOU Bridge | 4 span concrete girder bridge | Collapse |

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## 4.3 Highway Tunnels

### 4.3.1 Overview

Damage investigation of mountain tunnels was conducted at the two-mountain region around the earthquake-affected area caused by the 1999 Taiwan Jiji Earthquake.

One region is The Central; Highway Road(Taiwan Road No.8) along the basin of Da Jiaxi River from Dong Shi to Ma Ling which is located at about 40km～50 km north from the epicenter (Ji-Ji), and the other region is The Taiwan Road No.16,No.20 and No.14 along the basin of Zhuoshuichi River and Niao River from the epicenter of the earthquake Jiji to Riyue Tan and Kou Cheing, which are located about 10km～15km east and 20km north from the epicenter.

Damage investigation of the underpass at Shi shuikeng along the basin of Lao Zhuangxi River which is a branch of Da Anxi River was also carried out.

Figure 4.9,Figure 4.10 show the location of the investigation points.

### 4.3.2 Outline of damage

4.3.2.1 Mountain tunnels of The Central Highway Road (Taiwan Road No.8)

In this road, the damage investigations were carried out at five tunnels. Landslide and failing stones were widespread in the mountain region. Especially, up to Gu-Guan(谷關) region, many large landslides and rockfalls occurred which caused closure of the mountain roads. The major damage of the tunnel occurred at the portal due to the landslide around tunnel. Since, the earthquake faults crossing through tunnel, the significant damages of tunnel by fault slide were not recognized. The inner part of the tunnel did not suffer severe damage.

(a) Photo 4.51 shows the damage of The Li Leng mountain tunnel(Point 1) which is located near the Tienlun power plant. The landslide occurred in the basement rock around the tunnel, and the arch shoulder of portal suffered damages due to the landslide, but the inner part of tunnel suffered no significant damages.

(b) Photo 4.52 shows the damage of the portal of The Ma Ling No.2 tunnel(Point 2) which located at Ma Ling due to the large landslide which occurred at the basement rock surrounding the tunnel.

(c) Photo 4.53 shows the damage of the inner part of The Ma Ling No.2 tunnel. The cracks occurred in the circumferential direction on the side-wall due to the shear stress, and the drain ditches of tunnel suffered severe damages, and the concrete cover was broken by the compressive stress.

4.3.2.2 Mountain tunnel at The Taiwan Road (No.16.No.21 and No.14)
In these roads, the damage investigations were carried out at three tunnels. In this region, the large landslides and rockfalls did not occur and tunnel portals and inner part of the tunnels suffered no significant damage.

(a) Photo4.54 shows the Yu Le mountain tunnel (Point 3) located at Gan Zilin. The tunnel portal, inner part of the tunnel suffered no significant damage.

4.3.2.3 Damage of Underpass at Shishuikeng
The unreinforced concrete underpass at Shishuikeng with dimensions of 5.0m in length, 2.0m in width, 2.4m in height and the thickness is 0.2m, suffered heavy damage by the fault. At this point, the riverbed upheaved about 3.0m-5.0m.The underpass collapsed by shear deformation of the surrounding ground, and the open cracks occurred in the longitudinal direction on the sidewalls of the underpass shown in Photo 4.55(Point 5).

**4.3.3 Summary**

(1)The mountain tunnel suffered damages at The Central Highway Road due to the landslide. The major damage of the mountain tunnels was concentrated in the portal, and the inner part of tunnel suffered no significant damages.

(2)The underpass at Shishuikeng collapsed by shear deformation of the surrounding ground due to the fault.

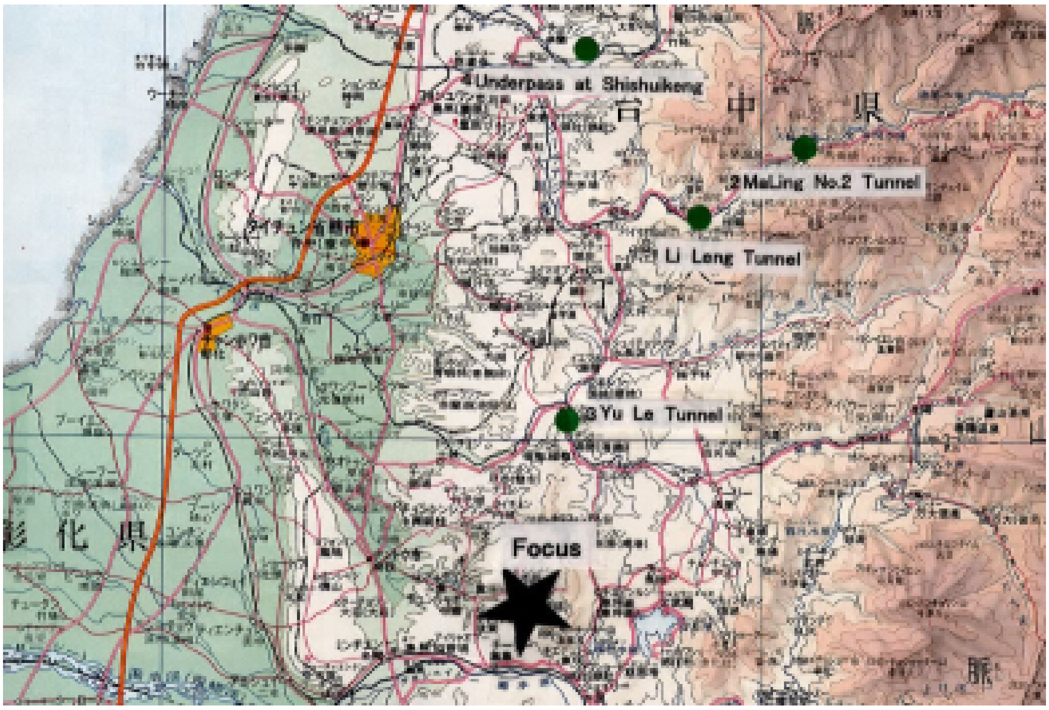


Figure.4.9 Location of Investigation Points

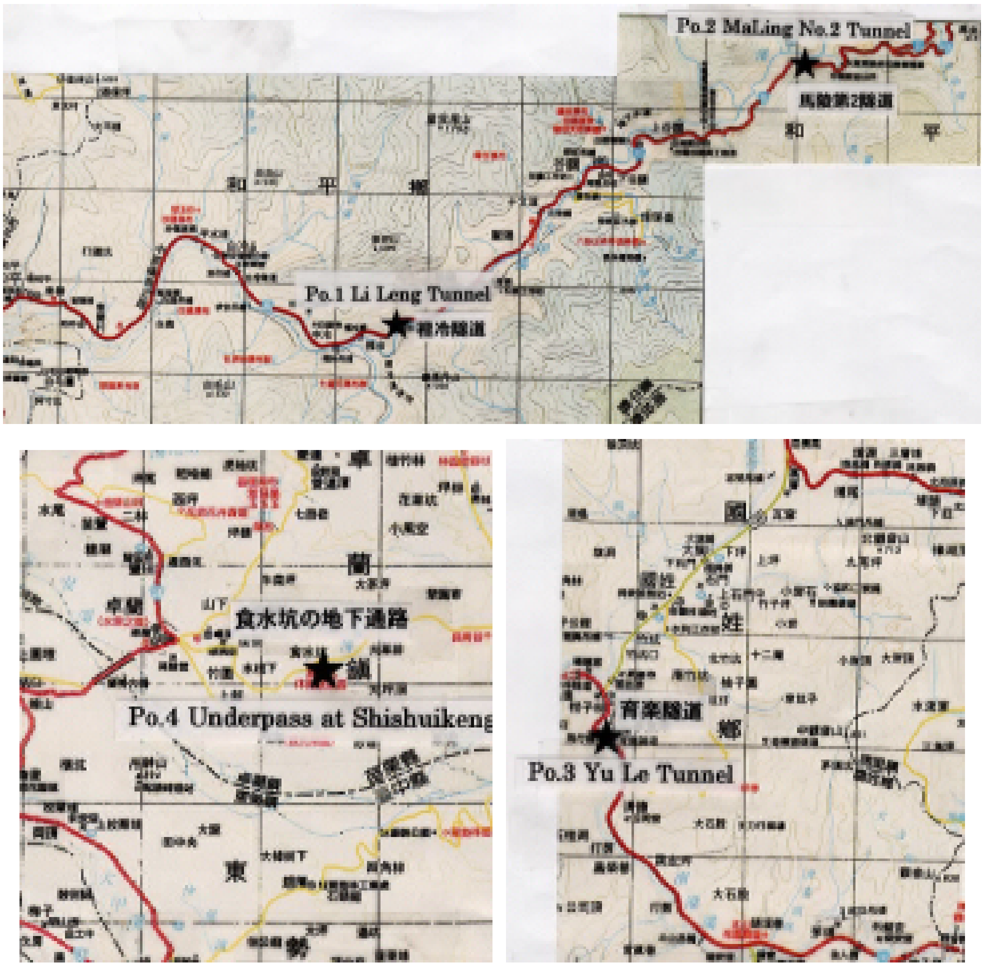


Figure.4.10 Location of Investigation points

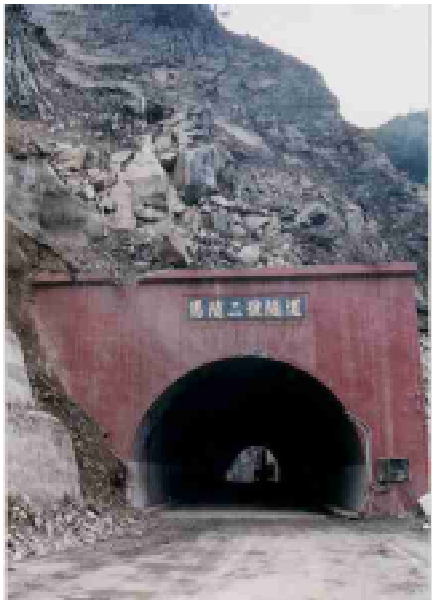

Photo.4.51 Damage of Li Leng Tunnel
(Taiwan Road No.8)

Photo.4.52 Damage of Ma Ling No.2 Tunnel
(Taiwan Road No.8)

Photo.4.53 Damageof Side wall at Ma Ling No.2 Tunnel(Taiwan Road No.8)

Photo.4.54 Yu Le Tunnel at Gan Zinlin
(Taiwan Road No.14)

Photo.4.55 Damage of Underpass at Shishuikeng

## 4.4 Damage and Restoration of Railway Facilities

### 4.4.1. Overview

The damage and restoration of the railway facilities were investigated. The investigation examined local damage and the restoration situation in detail. During the investigation, the damages of the railway facilities were discussed with Taiwan Railway Administration, and Ministry of Transportation and Communications Bureau of Taiwan High Speed Rail. Additionally, discussions on the seismic design for restoration, seismic retrofit of facilities, and the implication of the damage of the extremely large earthquake such as this one were made. This section reports the damage of the railway equipment of the earthquake, restoration, and the problem of the seismic design of the railway structure in the future.

### 4.4.2. Damage and restoration of railway facilities

The damage of the railway facilities due to this earthquake was relatively minor when it is compared with electricity, water service, or the road facilities, etc. However, the total damage of the railway facilities became about NT$390,000,000 (1,400,000,000 yen).

Western mainline (sea line) on the Taiwan west side which is an important trunk line was not interrupted immediately after the earthquake because it received no damage. However, Western mainline (sea line) operated with intermission for 10 days due to electric power shortage owing to the damage of the power plant after the earthquake.

Outline of the damage of the railway facilities is as follows. The lines in the Taiwan railway are indicated in Figure 4.11.

#### 4.4.2.1 Damage in Western mainline (mountain line)

Western mainline (mountain line) has been upgraded for the purposes of the speed improvement of the train and the life-elongation measures of facilities. Especially, railway facilities between Chunan and Fong-Yuan were newly constructed. The completion was October 1998 (Figure 4.12).

In the mountain line which had been newly constructed, two facilities received damage. One was "Dai-jia river bridge (digit type elevated bridge)", and another one was "San-yi tunnel. "

In the recovery process, original opening schedule was October 15. However, it was restored eariler on October 8 by urgent work by making use of the recent technological development of Taiwan National Railways.

**(a) Dai-jia river bridge (digit type elevated bridge)**

Basic structure of an elevated bridge is as follows.

・Double-track line (electrification line)

・Digit type elevated bridge (RC simple digit four main girders and span 25.0m×29 reams)

・725m in total length

・28 piers (pillar section φ3.2m)

・Caisson foundation structure (L=20.0m)

・The performance of the ductility is considered in the design of the pier.

Damage situation is as follows.

・In the pier, the pillar section and the projection part were damaged, and the rail buckling was generated too.

・The caisson foundation is not damaged.

・There were 12 damages of the pier pillar section.

・Some moment cracks (a part of shear crack) were induced from the ground level in the part of +1.0m.

・The crack width is 1.0mm or less. However, main reinforcement bars are supposed to be yielded.

・At one pier, shearing crack was formed at the connection of the beam-column part.

Retrofit of the pier is as follows.

・Retrofit of the column section of the pier has been done for the four piers where damage is comparatively large. The remaining 8 piers with small damage will be retrofitted later.

・Retrofit of the pier is RC lining (thickness of tunnel lining 30.0cm and longitudinal reinforcement D22ctc.13.0cm and tie-hoops D9ctc.10.0cm), and covers the steel board (9.0mm in the thickness of the steel board)(Photo 4.56).

・The beam part in the pier is covered by the carbon fiber after epoxy resin is injected into the crack (Photo 4.57).

・In the design of this bridge, it was assumed that the restoration at the early stage should be possible
even if damage was received by the big earthquake (L2 earthquake motion).

・Consequentially, the seismic earthquake performance of the pier can be considered as satisfactory.

**(b) San-yi tunnel**

Basic structure of the tunnel is as follows.

・Double-track line (electrification line)

・Construction technique: NATM (New Austrian Tunnelling Method)

・In selecting the route, the locations where a big ground deformation is expected due to fault motion is avoided (Figure 4.11).

Damage situation is as follows.

・Damage was found at three locations (vicinity of 161K, vicinity of 164K, and vicinity of
165K630m), 8 segments (Photo 4.58) in total.

・Spalling of the concrete block in the tunnel, fall of the trolley line, and the rail buckling.

・Horizontal displacement of the tunnel was about the maximum 2.0cm. The rail deformed at
maximum 74.0cm horizontally due to buckling.

Retrofit is as follows.

・After the backfill grouting is made, rock bolt reinforcement (L=3.0m, φ 30mm,ctc.1.2m) and the
shotcrete are done.

The original route plan was changed as a result of a detailed subsurface exploration and prediction of the fault action to avoid large deformation due to fault, although the length of route is extended considerably. Hence, the tunnel received only minor damage in this earthquake and interruption of closure was minimum.

**4.4.2.2 Damage in Taichungkang line**

Taichungkang line is a branch line from the sea line to the port.

Differential settlement of the railway track and rail buckling were generated due to liquifaction of the ground. Taichungkang line will not have been restored until the end on October 1999.

#### 4.4.2.3 Damage of Chi-Cii line

Chi-chi line is a branch line of the mountainous area.

The damage such as the rail buckling and liquifaction occurred widely in this. Especially, the ground deformation caused by the fault crossed the bank of the approach of the west side of a 5m span bridge in Mingchien district (Taichung city). Therefore, the railway track has upheaved by about 8.0m. The rail was dragged to this upheaval and moved (Photos 4.59,60). The displacement generated the buckling of about 4m in a right-angled direction of the rail.

Restoration was prepared by part. However, restoration is interrupted temporarily, and temporary schedule for full restoration is about March 2000.

#### 4.4.2.4 Damage of station

Ji-Ji station received severe damage close to collapse due to the earthquake. It is scheduled to repair and to be preserved, because it is the oldest historical wooden station in Taiwan constructed in 1930(Photo 4.61).

The Taichung station (cultural asset specification), is being repaired for the cracks in the column (Photos 4.62,63).

#### 4.4.2.5 Damage of Mt. Ali forest railway

In Mountains railway of Mt. Ali forest line, damage due to the landslide and ground failure was observed. It also collapsed the sightseeing spot, the head of famous Monkey rock (dharma rock). It is said that 4-6 months are required for restoration.

#### 4.4.2.6 Damage of old railway bridge (Present; pedestrian bridge)

The bridge on Da-Jia river in Dongshi line (branch line in the mountain line) which became a disused line eight years ago is being used as a pedestrian bridge now (Photos 4.64). This bridge was constructed in 1930's. The bottom part which connected with the upper part of the pier breaks due to the earthquake, and the anchor bolt of bearing in the abutment part has been broken. This bridge did not drop though it was a district where a violent earthquake motion was received. This may have been due to rigidity of deck plate girder, light slab (steel), and relatively low height of bridge girder.

### 4.4.3 Problem of seismic design of railway structure in the future

The validity of the ductility design method "The structure should not collapse even when it is damaged due to a strong earthquake" was proven in a railway elevated bridge this time. It is important to set the appropriate ground motion considering the existence of a strong earthquake motion in the vicinity of the epicenter.

As for the feature of the earthquake at this time, severe damage was caused by the fault activity, and the seismic design in which the displacement of the fault is assumed will be an important. As measures of this fault displacement, the structure is not constructed or the method such as exceeding the fault section in the bridge of the long span is devised in the fault neighborhood. Moreover, it is possible to assume the fault part to be a earth structure (fill etc.), and to secure the restoration at the early stage if it can be thought that the probability to which the train is running in this vicinity is low even if the railway structure receives damage by the fault. For the case of lifeline structures such as railways, the fault is crossed inevitably. In addition peculiar problems to the railway is that travelling and the speed of the train on the railway structure. There is also a limit for the method employed at San-Yi Tunnel where large fault motion is avoided in case of the rapid-transit railway. Hence, further technical development will be required based on the lesson of this earthquake.

**4.5.4 Summary**

The damage of the railway facilities of the Ji-Ji earthquake appeared to be minor, however, one cannot overlook the effort of Taiwan Railway Administration who avoided places which is susceptible to fault in selecting new route. It became clear that not only strong shaking but also fault motion itself needs to be considered for near-field earthquakes.

In Japanese in Tokai-do and Sanyo Shinkansen UrEDAS (Urgent Earthquake Detection and Alarm System) has been installed as railway system for the prevention of disasters to secure the safety for the train against large earthquake under running. However, in addition, advanced structural design need to be employed for the crossing of fault to avoid collapse and to make early restoration possible.

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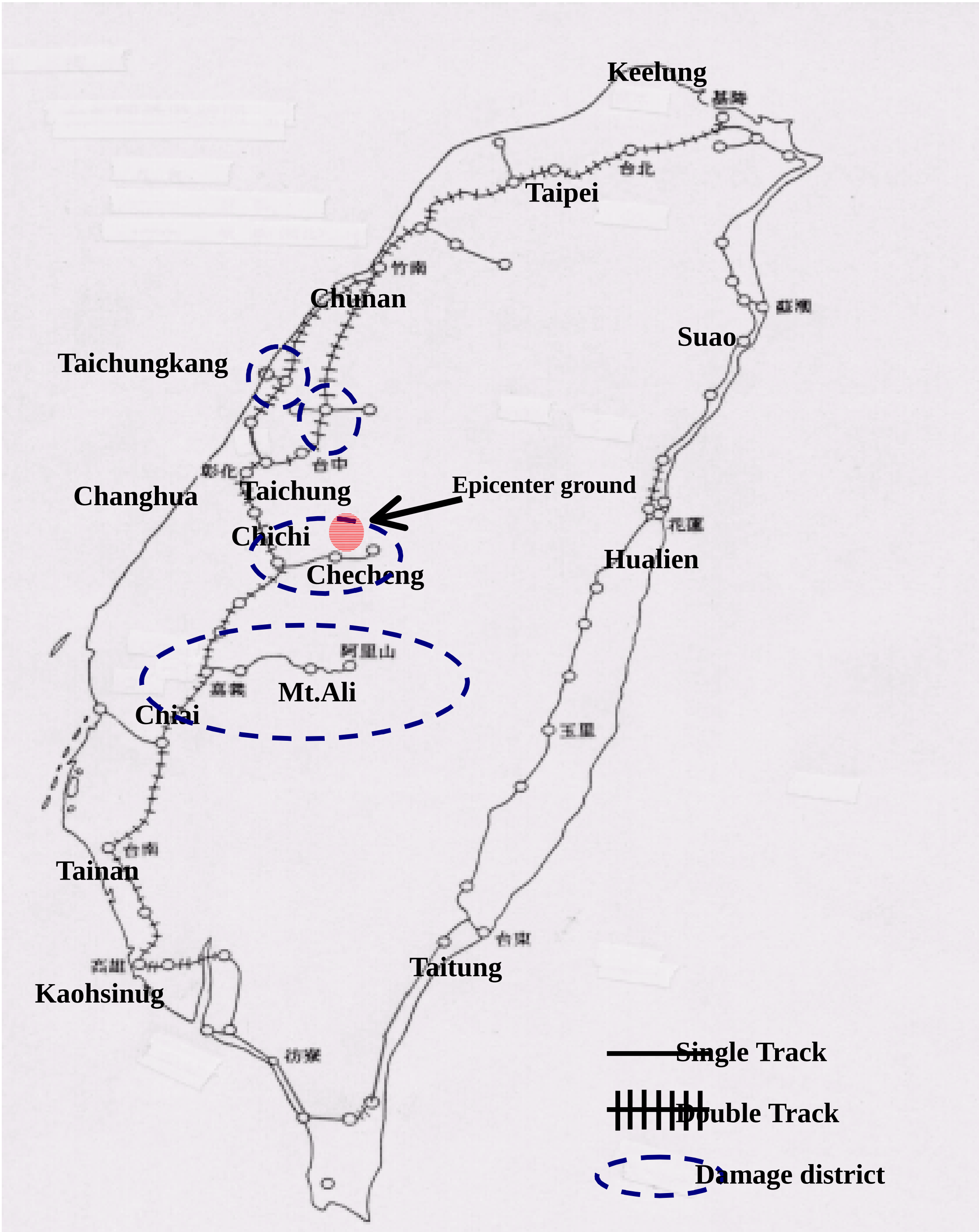


**Figure 4.11 Taiwan railway route**


**Figure 4.12 Western mainline (mountain line)**

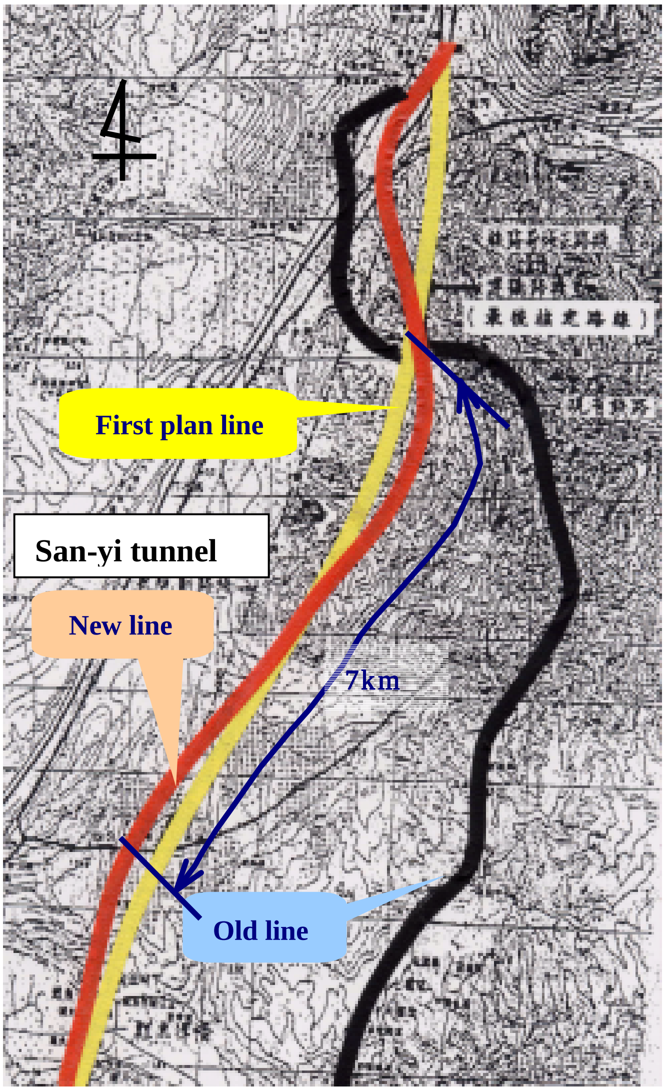


Figure 4.13　Plan of San-yi tunnel

**Photo 4.56 Reinforcement of elevated bridges**

**Photo 4.57 Reinforcement of projection part**

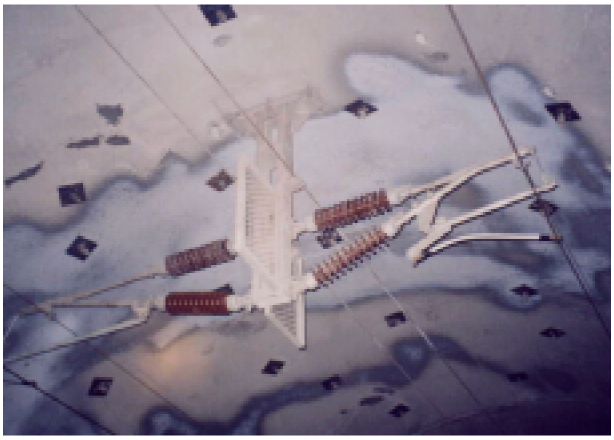

**Photo 4.58 Reinforcement of tunnel**

**Photo 4.59 Damage in Chi-chi line (Mingchien)**

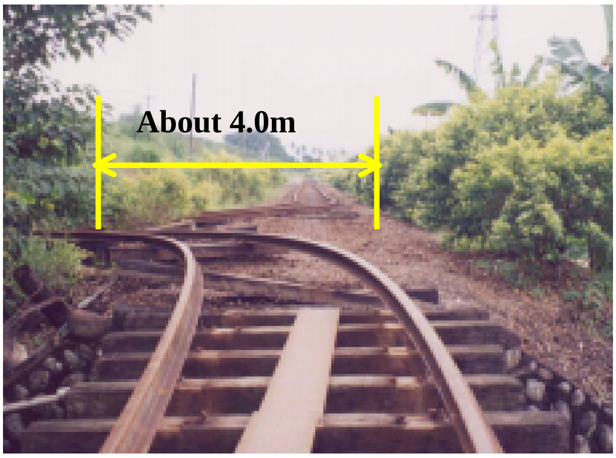


**Photo 4.60 Rail buckling**

**Photo 4.61 Chi-chi station**


**Photo 4.62 Taichung station**

**Photo 4.63 Reinforcement of Taichung station**

**Photo 4.64 Damage of old railway bridge**