

6. DAMAGE TO DAMS

The main island of Taiwan is spindle-shaped with a high mountain ridge extending roughly in its longitudinal north-south direction. The backbone ridge is the main water-divide between the east and west slopes of Taiwan. Several major rivers of Taiwan flow from this mountain ridge into the East China Sea. Among the rivers, the Da-Jia River, about 140km long with 6 dams and 3 largest hydroelectric generating plants, generates the largest amount of hydroelectric power in Taiwan. The flow of the Juo-Suei river, lying about some 50 km south of the Da-Jia River, is also quite abundant. There are 2 dams for hydroelectric power generation (Takuan and Mingtan) in this river system, and one weir (Ji-Ji) is being constructed across the main stream. The rupture of the Chelungpu Fault, which was originated in the vicinity of Ji-Ji town has traveled north across these rivers. This fault rupture changed its path quite abruptly towards the east in the vicinity of Feng-Yuan City, and ran across the Shih-Kang Dam constructed at the lower reach of the Da-Jia River.

The authors investigated four dams near the fault, the dams include Shih-Kang (Da-Jia River), Liyutan (Jing - Shan Shi River, a small branch emptying into Da-An River), Suei-Sheh (Ru-Yue-Tan Lake, Juo-Suei river system) and Ji-Ji (Juo-Suei River). Among them, the features of damage to the Shih-Kang Dam, where the fault has crossed the dam body, were extraordinary; the detailed description follows in Section 6.1.

6.1 Shih-Kang Dam

6.1.1 General View

Shih-Kang Dam, located about 100 kilometers southwest of Taipei, was built across the Da-Jia river where the river's fan-shaped plain begins to spread gradually towards the East China Sea (Figure 6.1). The dam site lies over a shallow sandy and gravelly soil deposit spreading over a laminated mass of mud stone, silt stone and sand stone of the Pliocene Epoch, Tertiary Period. The construction of the dam began with the excavation of this shallow sandy and gravelly soil deposit down to the underlying rock surface, and was completed in 1977.

The Shih-Kang Dam, 25 m tall and 357 m long with 18 gates lined up, has a total concrete bulk of 141,300 m³ (Figures 6.2, 6.3 and 6.4). The reservoir with the capacity of 3.38 million m³ collects water from a catchment area of 1,061 km² in the Chung-Yang Mountains, and provides a steady supply of water for irrigation and etc. An intake tunnel on the left abutment of the dam leads the water through a diluvial terrace down to the Feng-Yuan water-treatment plant.

The construction of the dam was preceded by some necessary geological investigations. The contours in Figure 6.5 describe the configuration of the base rock of the Tertiary period overlaid with sands, gravels and other suspended matters that the Da-Jia river has carried over centuries. Solid circles in the figure (DH. 1 – 14 on the line C-C, DH.101-107 on A-A and DH201-204 on BB) show the arrangement of the boreholes lined up along the dam axis. Figure. 6.6 shows the estimated soil and rock profiles across the river with the borehole data provided. Both two cross-sections AA and BB show that the base rock surface is quite shallow in the middle of the river bed, -3 to -4 m below the soil surface, and reaches -10 to -13 m depths on both sides. These sedimentary base rocks of the Tertiary period can be recognized with their stratified feature. The strata of these rocks run, in general, in about N40°E-40°S direction, and meet the dam axis at an

angle of 60 degrees. The strata planes have a dip of about 40 degrees down towards southwest. Hammer blows on these rocks do not create any sharp sounds, suggesting that the compressive strengths of the rocks are some 100 kgf/cm² or less. When the base rocks were exposed after the excavation for constructing this dam, no clear evidence of the presence of a fault was found (Water Resources Bureau, Ministry of Economic Affairs, Taiwan).

6.1.2 Features of Fault and Fault-Related Damage to Dam Facilities

Figure 6.7 is taken from “An Introduction to the Active Faults of Taiwan”, Central Geological Survey (CGS), Ministry of Economic Affairs, Taiwan. The CGS has confirmed that 51 active and/or suspicious faults longer than 5 km exist, and are classified as follows:

- (1) 1st category active faults:
 - a) activated at least once in the past 10,000 years,
 - b) having caused some damage to existing structures,
 - c) responsible for earthquake occurrences,
 - d) having deformed alluvial soil deposits, and
 - e) whose presences are clearly recognized from surface geological configurations.
- (2) 2nd category active faults:
 - a) activated at least once in the past 10,000 years, and
 - b) having deformed diluvial terraces.
- (3) Suspects:
 - a) with ambiguous features in Quaternary configurations,
 - b) with ambiguous features in laterite soils, and
 - c) looking alike but without any clear evidences.

The activated fault (red thick line) seems to have appeared exactly along the Chelungpu Fault, of which presence had been already recognized, and classified into the 2nd category of active faults. The activated fault however appeared branching east off the recognized trace of the Chelungpu in the vicinity of Feng-Yuan City, and crossed the Shih-Kang area. The activated fault, in this chapter hereafter, will be referred to as the Chelungpu Fault.

The complicated features of this fault emerge as the Shih-Kang area is zoomed in on. Figure. 6.8 shows the offsets that the authors have found during their reconnaissance. In this figure, the line, A, forms a part of the northeast extension of the Chelungpu Fault. The line, A, has crossed the Da-Jia river near the Bei-Fon bridge, where the southeast side of the fault has risen up by about 6 m with respect to the other side, causing a water fall to have appeared (Figure. 6.9). This line, however dies out as it climbs the north mountainside, and another line, C, appears abruptly a couple of hundred meters south off the line, A. This line, C, has crossed the northern end of the Shih-Kang dam causing three spillways of the Shih-Kang dam (No. 16-18) to be severely destroyed. The Water Resources Bureau, Ministry of Economic Affairs, who maintains and operates this dam, took quick action of surveying the damaged dam site and its vicinity for its retrofitting, and the elevations of a number of points were measured. Among them, two points were put side by side on the dam in such a way that the line, C, runs exactly through the two points, one on the pier No. 15 (Point *a*) and the other near by the gate No. 18 (Point *b*). Table 6.1 compares the elevations of these two points before and after the earthquake.

Table 6.1 Elevations of Points *a* and *b*
(Water Resources Bureau, Ministry of Economic Affairs)

	(1) Elevation after EQ	(2) Elevation before EQ	(1) – (2)
Point <i>a</i>	283.05 m	272.00 m	11.05 m
Point <i>b</i>	273.01 m	272.00 m	1.01 m

From this table, it is clear that the south side of the line, *C*, has risen up by about 10 m with respect to the north side. The entire picture of the fault line, *C*, however, is not clear yet, because the most part of the line lies under water. The estimated line, thus, is shown with the in-convincingly curved broken red line in Figure 6.8. The following findings, however, allow the authors to draw the broken line.

(1) The reservoir bed has risen up in its south half (left side of the dam) slightly above the water level, whereas no clear marks showing the varying water level is found on the right shore slope of the reservoir.

(2) Just below the dam, the right riverbank has settled down over a couple of ten meters distance, and the trees behind the riverbank were deeply dipped in the water that must have flowed in there. The extension of this depressed ground seems to climb up the mountainside, and

(3) a remarkable vertical offset of a road appeared on this extension.

In addition to the faults *A* and *C*, another fault line, *B*, appeared on the south side of the Da-Jia River. As a whole, the north side of the line, *B*, has risen up by several meters, that is to say, the entire area surrounded by the lines *A*, *B* and *C* was relatively pushed up to that noticeable extent. This line, *B*, has crossed the intake tunnel of the Shih-Kang Dam, shearing the tunnel completely. Figure 6.10 shows the tunnel dug out after the earthquake. The tunnel has an oval cross-section, 4.1 m and 3.8 m in upright and transverse diameters, respectively. The roof line, which is clearly recognized with the steel timbers meeting together, was cut in half, showing the extent of the dislocation which the tunnel experienced. At this site as well, the Water Resources Bureau measured the elevations of some points around the sheared tunnel. Table 6.2 shows the comparison of the elevations of two points (Points *c* and *d*) arranged side by side on both sides of the fault.

Table 6.2 Elevations of Points *c* and *d*

	(1) Elevation after EQ	(2) Elevation before EQ	(1) – (2)
Point <i>c</i> (north)	262.36 m	256.24 m	6.12 m
Point <i>d</i> (south)	258.85 m	256.24 m	2.61 m

The vertical offset there is found to be about 3.5 m from the table, and judging from Figure 6.10, right lateral slip seems to be about 3 m. All tunnel joints cracked seriously (Figure 6.11). Large pieces and small fragments of concrete came off the tunnel wall, and the slack of the roof cable evidences that the tunnel has experienced a large axial force. The large axial force seemingly punched out the intake gate wall by about 20 cm (Figure 6.12).

The fault, *B*, was also responsible for damming up the Shyh-Suei-Keh Shi River, a small branch of the Da-Jia River. At this place, the north side of the line, *B*, a sedimentary rock mass, has risen up by about 4 m dragging up a soft soil deposit of silt, sand and boulders, and thus, causing houses on it to tilt to the south. A ditch was immediately dug through this sedimentary rock mass to let the dammed up water flow into the Da-Jia River.

6.1.3 Damage to the Dam Body

As has briefly mentioned above, the Shih-Kang Dam has suffered serious damage mostly due to large dip-slip movement of the fault line, *C*. Figure 6.13, a sketch of the dam made from behind, shows slightly tilted spillways #15 and #16, seriously slanting spillways #17 and #18, the latter is deeply dipped in the water stopped behind. All these dislocated spillways allow us to figure out a possible shape of dislocation that happened immediately beneath the dam. It is noted in this sketch that spillways #16 and #17 slant to the left and right, respectively, indicating that the left side rock gradually rises towards the upper end of the fault-created steep scarp. Figures 6.14 and 6.15 were photographs taken from the downstream riverbed and the right abutment, respectively. From Figure 6.15, it is found that not only the large dip-slip movement but also a left-lateral movement reaching about 3m took place. The north part of the dam between the spillway #18 and the right abutment were cracked up along construction joints into several huge blocks, and a considerable amount of water was leaking out through the cracks.

Rock masses on both sides of a fault do not move as rigid bodies as was illustrated in the sketch (Figure 6.13). Since the dam was constructed directly upon the base sedimentary rock mass, the pattern of cracks on the dam body might indicate how the base rock was deformed during the earthquake. The cracks on the spillways and aprons were closely mapped (Sugimura and Jyh³), Figures. 6.16-6.22). Needless to say, cracks on such parts as those lying under water were excluded from these figures. Those excluded include the upstream slopes of spillways behind gates, and the spillways with their gates open. The completely destroyed spillways #16-18 were also excluded from this mapping.

Figure 6.16 shows the distribution of cracks over the entire extent of the dam. The dam is made up of 21 blocks whose numbers are put in circles in Figure. 6.16. A pier sticks upright in the middle of a block, and a pair of blocks put side by side forms a spillway. Major cracks on spillways were found between the spillways #6 and #16, namely on blocks - . In general, diagonal cracks were found on most damaged spillways, and transverse joints between blocks were opened in such a way that the openings on the upstream side were wider than those on the downstream side (Figure 6.17). The entire dam body thus seems to have been slightly bent towards downstream side. The most diagonal cracks except those found on blocks and reached piers as shown in Figures 6.17 and 6.18. Cracks along horizontal construction joints were found on four piers #9, #10, #15 and #16 (Figure 6.19). No major cracks were found on blocks - , more than 160 m away from the fault, *C*. In this less-damaged part also, Piers #1-#5 were found cracked. The cracks on Piers #1-#5, however, have some different features from those found on the piers closer to the fault *C*. Some small fragments of concrete came off a jagged horizontal crack on Pier #2 (Figure 6.20), and the upper construction joint of Pier #3 was cracked as illustrated in Figure 6.21. A crack that has developed diagonally up through Pier #1 is illustrated in Figure 6.22 whereas the crack found on Pier #5 seems to have developed upright from the similar position. These cracks on the dam body have caused 6 gates not to be operable.

6.2 Liyutan Dam

The Liyutan Dam, a center-cored rockfill dam of 96 m high and 235 m long, is located about 7 km north of the Shih-Kang Dam (Figure 6.23). The plan and the transverse

cross-section of the dam are shown in Figures 6.24 and 6.25, respectively. The construction of the dam across the Jing - Shan Shi River, a small branch of the Da-An River was completed in 1992 with seismometers installed at five different points on the dam (T1-T4) and in its vicinity (on an outcrop of rock) as shown in Figure. 6.26. Table 6.3 shows the peak accelerations obtained from the seismometers on rocks.

Table 6.3 Peak accelerations (cm/s²)
(Water Resources Bureau, Ministry of Economic Affairs)

	Longitudinal	Transverse	Vertical
Rock crest	150.4	119.8	144.6
Outcrop of rock	101.9	50.84	97.3

Since no seismometer was installed in the Shih-Kang Dam, the obtained accelerations will be of some help for us to go on further detail discussions. Figure 6.27 shows the peak values of acceleration observed in the 1995 Kobe Earthquake on both rock outcrops and soil sediments; the accelerations are plotted with respect to the distance from the nearest fault rupture plane beneath Kobe City. The outcrop acceleration observed at Liyutan Dam site, when plotted on this figure, seems to fall in the possible range of scattering.

Only a transverse crack was found on the boundary between the left abutment and the dam. Its maximum opening and vertical offset were 4 ~ 5 cm and 3 ~ 5 cm, respectively. Except that, nothing particular was seemingly found there. The earthquake was followed by a slight and temporary increase in water leakage as shown in Table 6.4, but the leaking water remained clear.

Table 6.4 Water leakage (Liyutan Dam)

Date	Water elevation (m)	Leakage (l/min)
Sept. 20	269.48	90.8
Sept. 21	268.96	104.5
Sept. 23	268.50	111.8
Sept. 26	267.67	101.0

6.3 Suei-Sheh Dam

The Suei-Sheh Dam, a center-cored earthfill dam of 30.3 m tall and 363 m long, has a total soil volume of 694,000 m³ (Figures. 6.28 and 6.29). This dam, located about 13 kilometers east of the epicenter, and about 21 km east of the nearest rupture fault plane, was built across a depressed configuration along the Ru-Yue-Tan Lake, where the water of the lake flowed over into a small river leading to the Juo-Suei river. The construction of the dam began in 1918, and was completed in 1934, before the World War II.

A longitudinal crack was opened over a 175 m distance on the crest of the dam (Figure 6.30). The maximum opening of the crack reached approximately 5 cm. The cracked crest was pitted to measure the crack depth, which was found to be about 40 ~ 50 cm deep. Concrete slabs covering up the upstream slope have been slightly slipped causing their horizontal joints to be opened by about 3 ~ 5 cm. A slight increase of water leakage of about 20 l/min reportedly followed the earthquake, but the leakage was recovered by reducing the water level to some allowable extent.

6.4 Ji-Ji Weir

Ji-Ji Weir, located about 50 kilometers south of Shih-Kang Dam, is being built across the Juo-Suei River where the river's low-lying plain begins to spread (Figure 6.31). The stream flow of the Juo-Suei River, carrying a heavy load of suspended matter, is quite different in wet and dry seasons. Most of the stream flows, about 71 to 87% of the annual amount, occur in the wet season, from mid-May to late October, and often wash away diversion facilities along the river. To minimize the damage and to provide a steady supply of water for public and industrial use, the project of constructing the Ji-Ji Weir was carried into effect in 1993. The weir, 30.3 m tall and 352.5 m long with 18 tainter gates and 4 sluice gates lined up, lies directly on a laminated mass of sand stone and slate of the Tertiary Period.

The intense shake caused its gallery to be flooded above the floor level, and the water was being pumped out. Some precast concrete beams spanning gates fell sideways. There are two intake channels under construction along both sides of the Juo-Suei River. About 4~5 km west of the weir, the southern part of the Chelungpu Fault crossed the south intake channel causing it to be cut in half immediately beneath the Ming-Juu Bridge (See Chapter 4). The vertical dislocation there reached 4 m.

6.5 Summary

The rupture of the Chelungpu Fault, which was originated in the vicinity of Ji-Ji town has traveled north across rivers flowing from the Taiwan's central mountain ridge into the East China Sea. This fault rupture changed its path quite abruptly towards the east in the vicinity of Feng-Yuan City, and ran across the Shih-Kang Dam constructed at the lower reach of the Da-Jia River. The features of damage to the Shih-Kang Dam were thus extraordinary. The fault's vertical dislocation, reaching about 10 m at the northern end of the dam, caused three spillways near the right abutment to be severely destroyed. Another fault branch that appeared on the south side of the Da-Jia River has crossed the intake tunnel of the Shih-Kang Dam, shearing the tunnel completely. Compared with the features which the fault dislocation was the most responsible for, the other dams near the fault were slightly damaged due to an intense shake. The accelerations obtained from Liyutan Dam for example will be of some help for further detail discussions.

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- 2) Blue prints of the Shih-Kang Dam, Water Resources Bureau, Ministry of Economic Affairs, Taiwan.
- 3) Sugimura, Y. and Jyh, S. G. (1999), Crack Map of the Shih-Kang Dam, Japan Dam Engineering Center and Central Water Resources Bureau, Ministry of Economic Affairs.

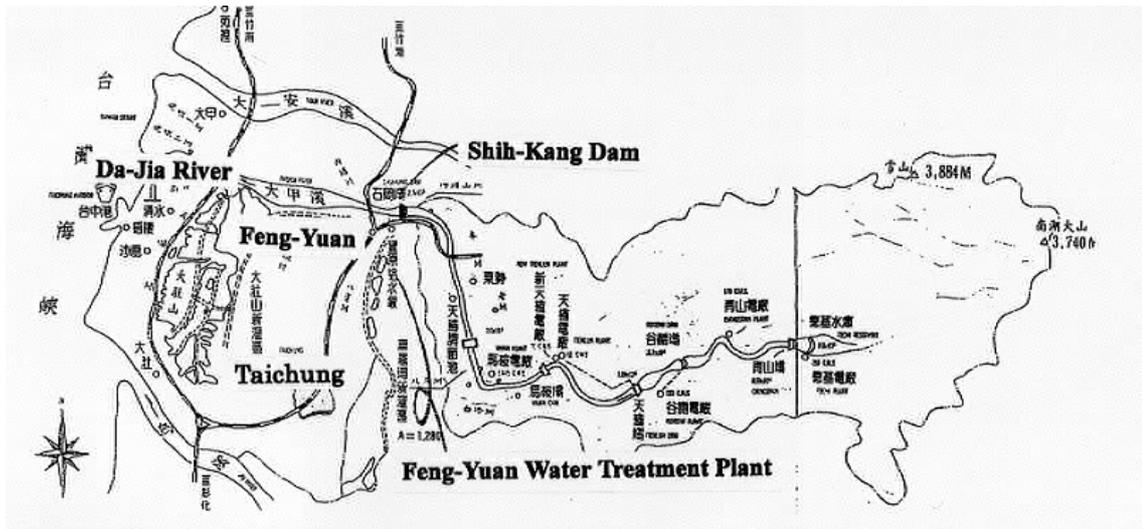


Figure 6.1 Location of Shih-Kan Dam



Figure 6.2 Shih-Kang Dam (before Earthquake)
 Broacher of Shih-Kang Dam: Committee for maintenance of Shih-Kang Dam, 1994

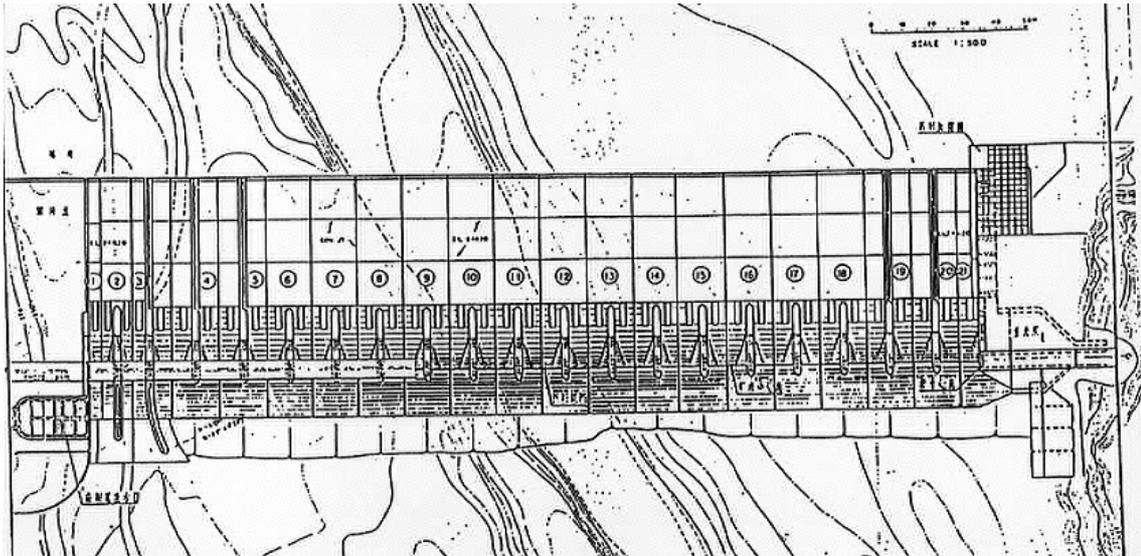


Figure 6.3 Plan of Shih-Kang Dam

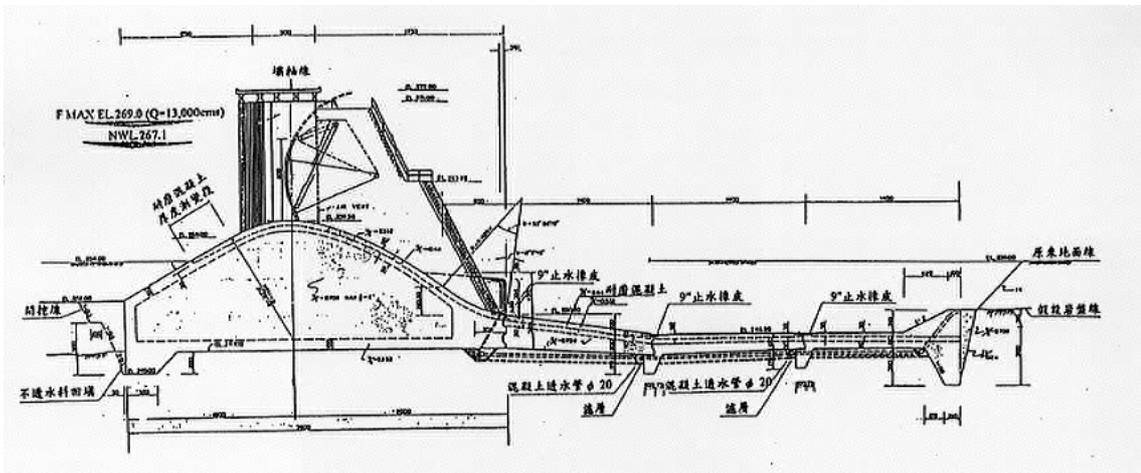


Figure 6.4 Cross-section of Spillway

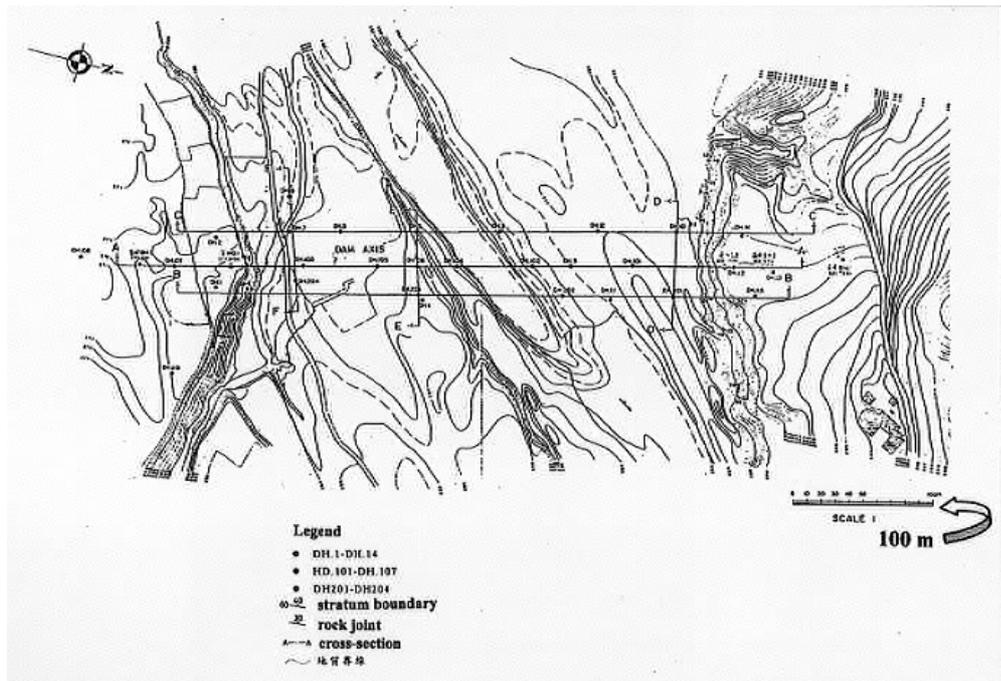


Figure 6.5 Arrangement of boreholes

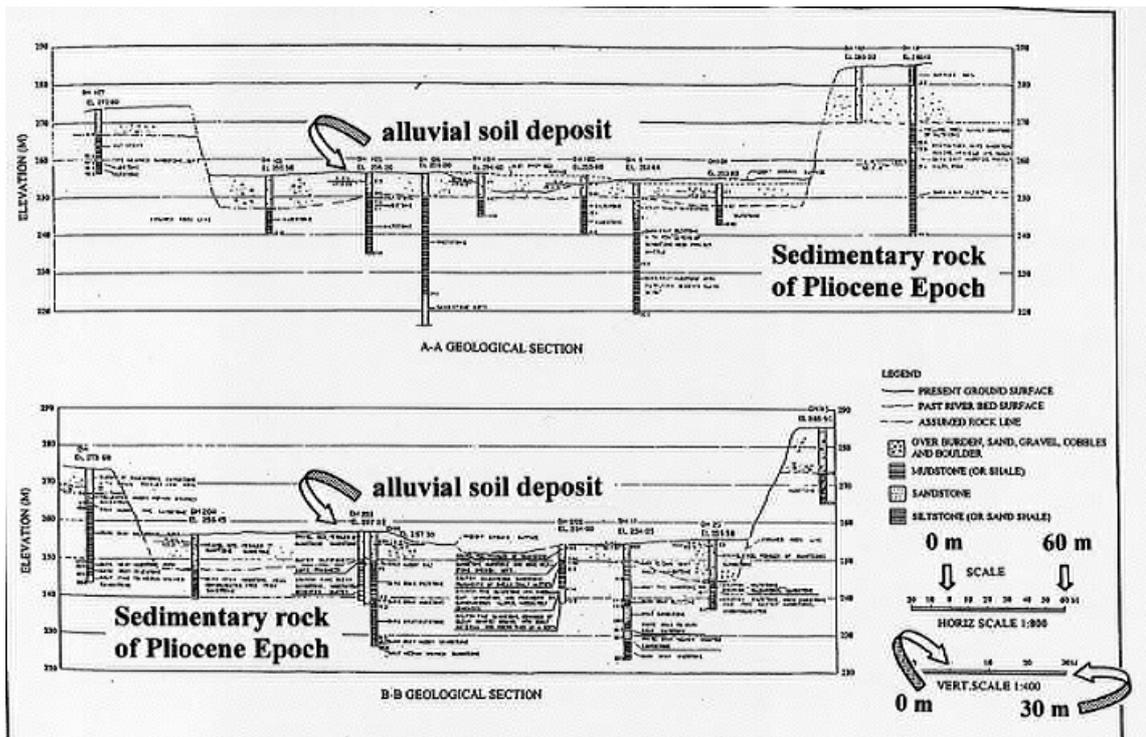


Figure 6.6 Geological sections across Da-Jia River

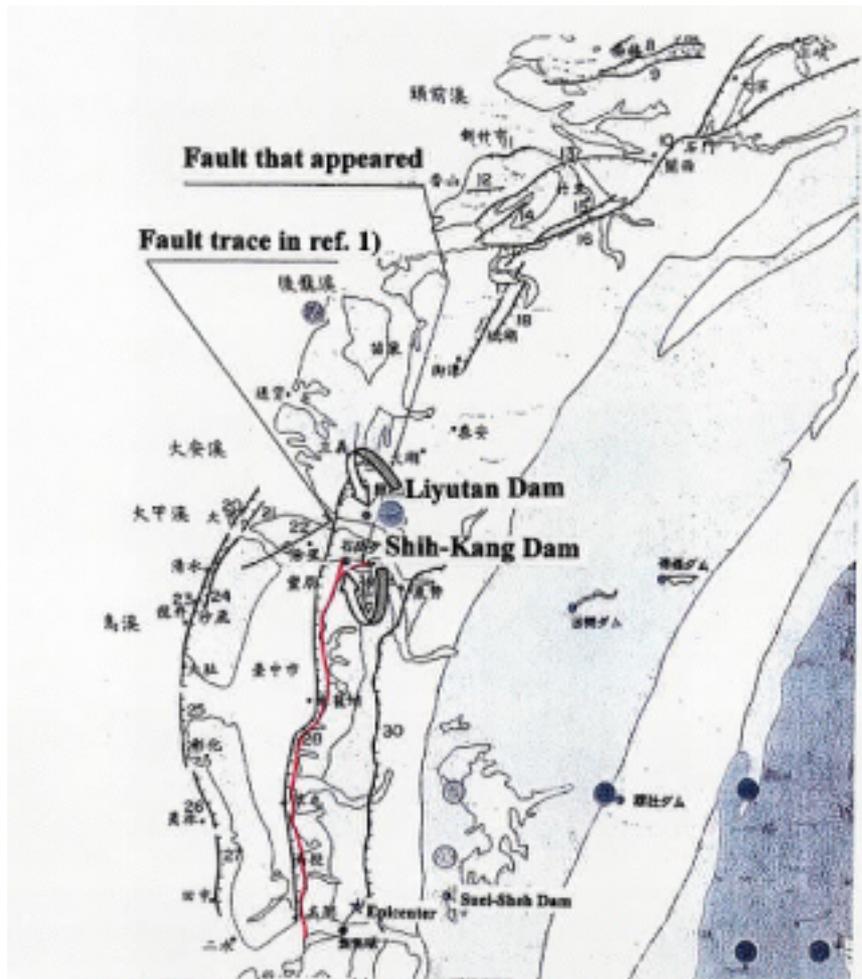


Figure 6.7 Chelungpu fault

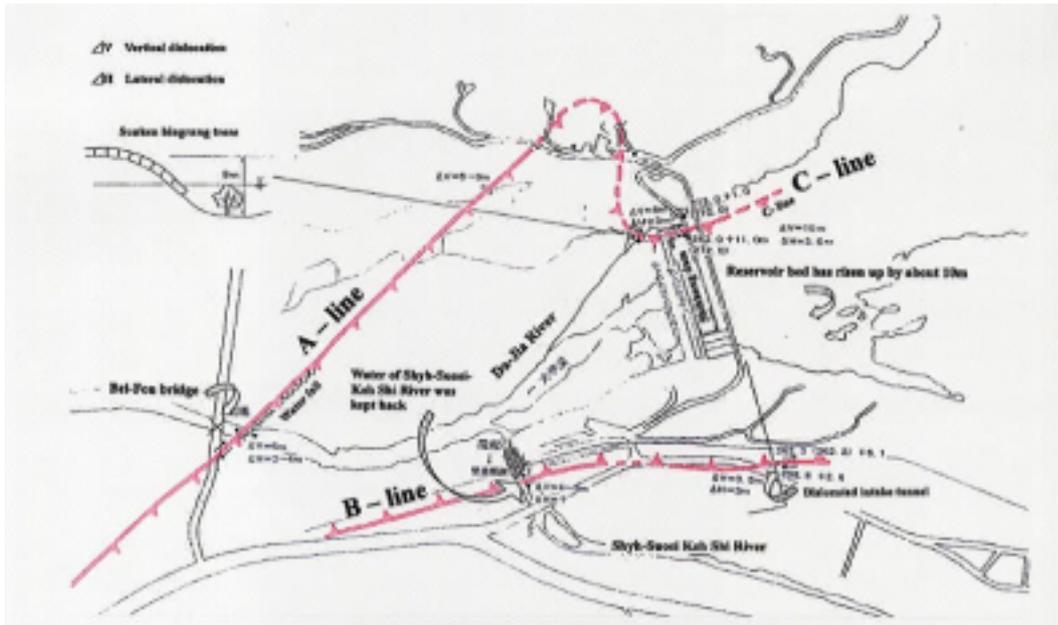


Figure 6.8 Shih-kang Dam and its vicinity



Figure 6.9 Bei-Fon Bridge and fault-created waterfall

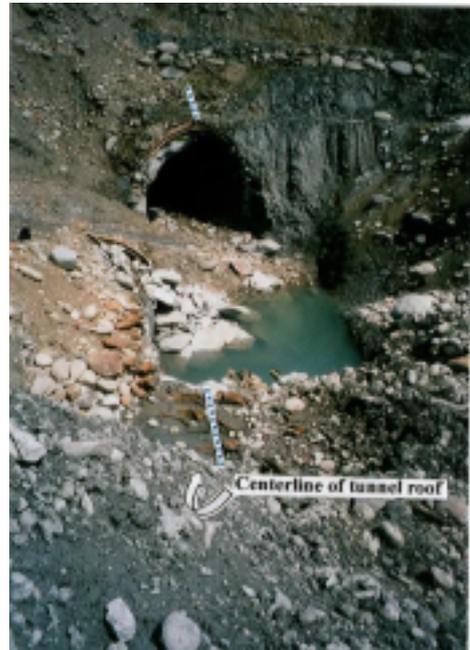


Figure 6.10 Sheared intake tunnel



Figure 6.12 Intake gate wall



Figure 6.11 Cracked tunnel wall

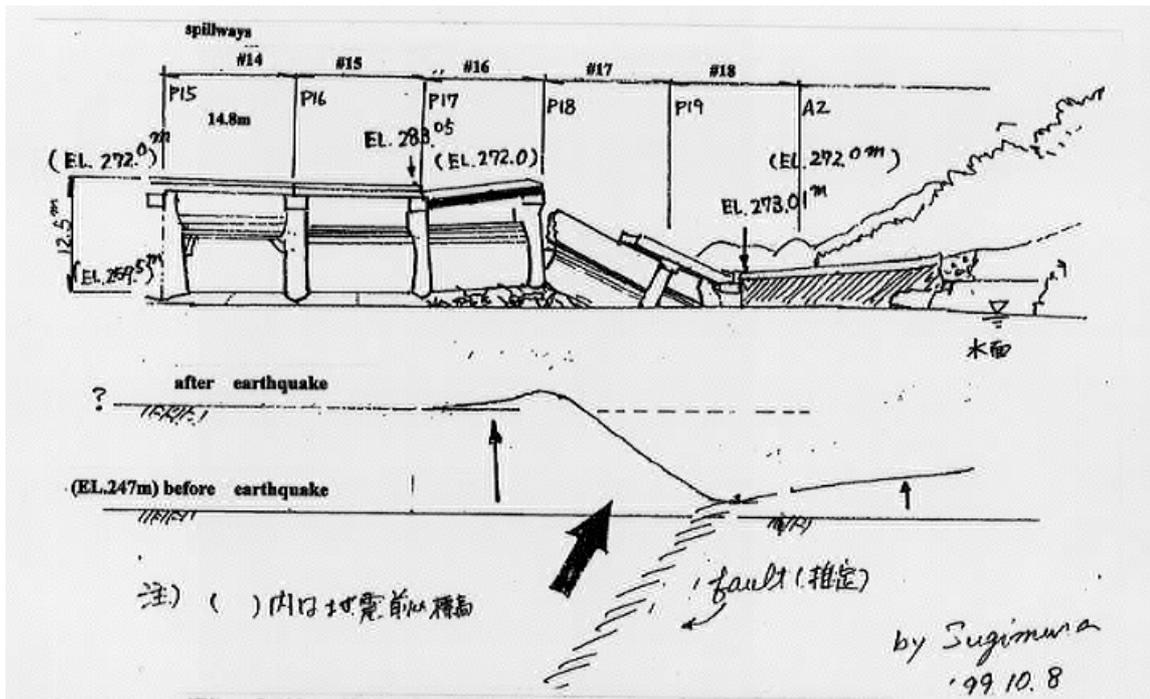


Figure 6.13 Sketch of Shih-Kang Dam from behind



Figure 6.14 Broken spillways of Shih-Kang Dam
(Photos taken from downstream side)

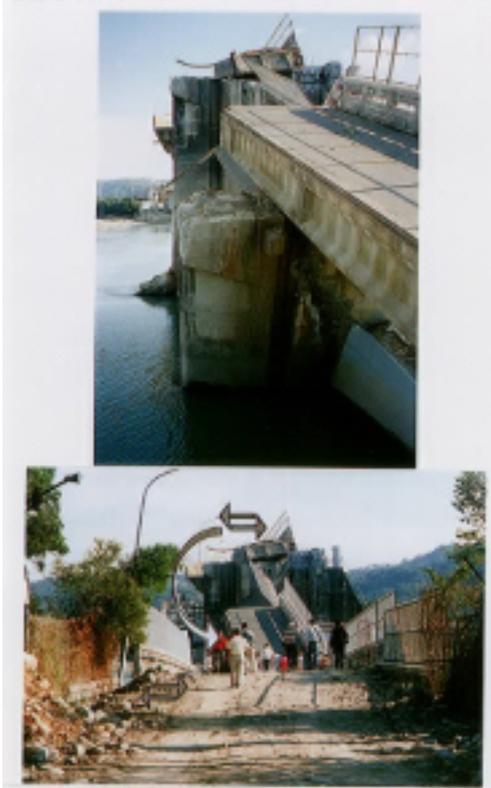


Figure 6.15 Broken spillways of Shih-Kang Dam (Photos taken from right abutment)

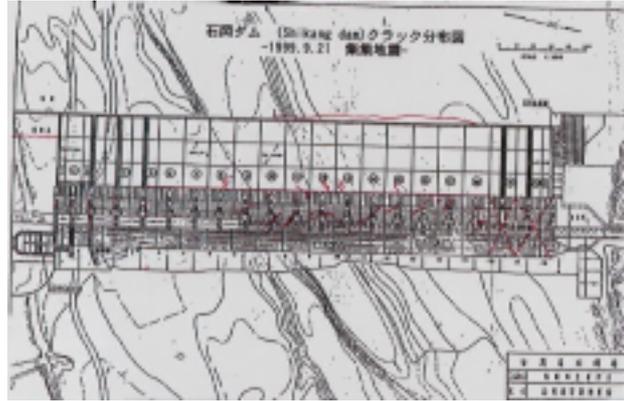


Figure 6.16 Crack map of Shih-Kan Dam

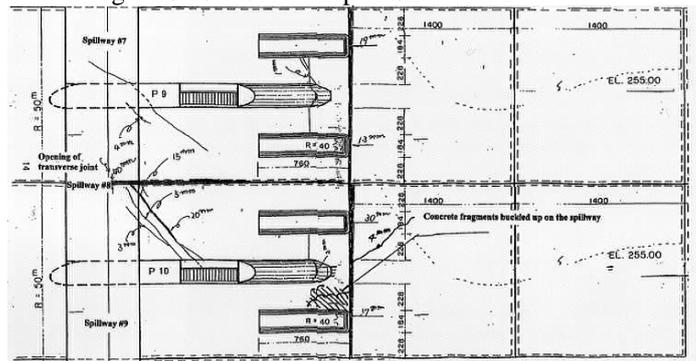


Figure 6.17 Crack on Blocks and

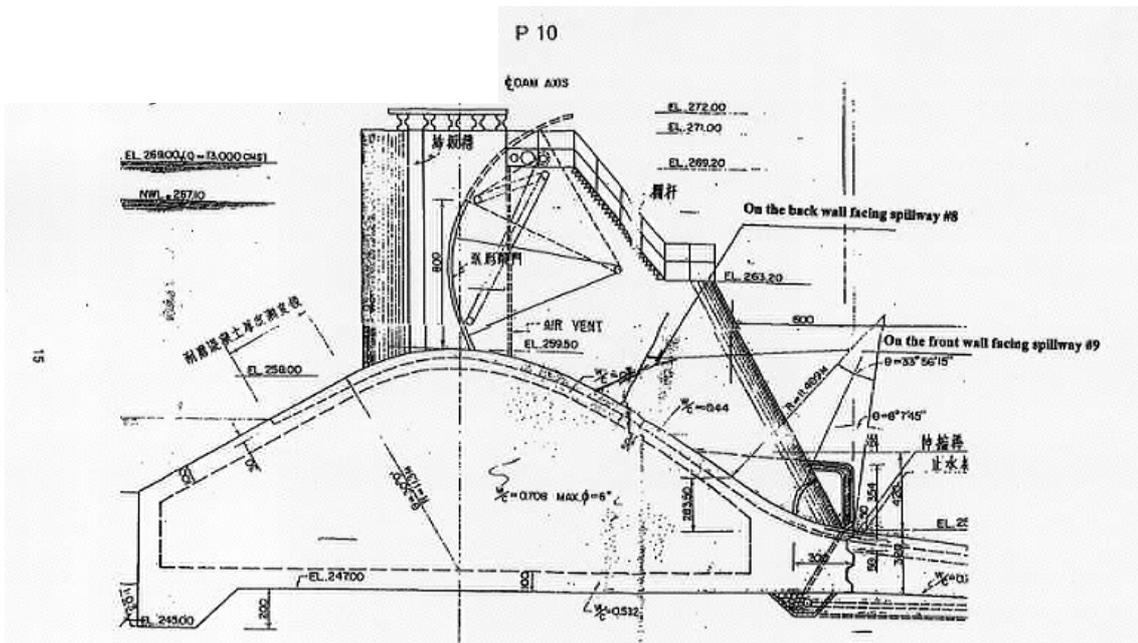


Figure 6.18 Cracks on Pier #10

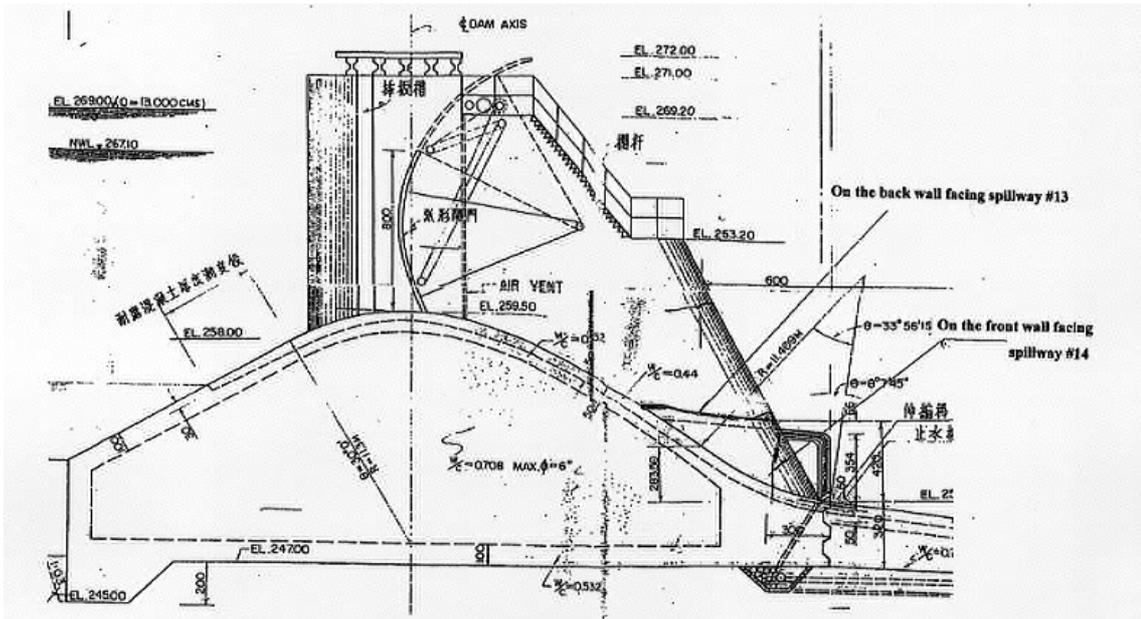


Figure 6.19 Cracks on Pier #15

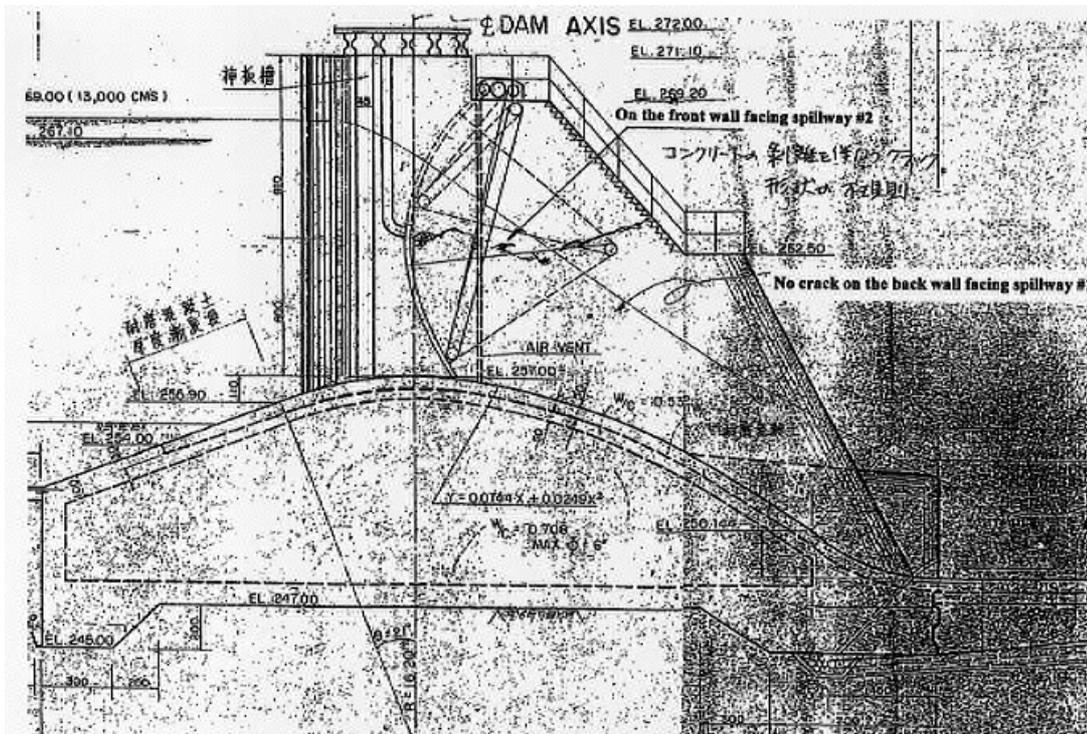


Figure 6.20 Cracks on Pier #2

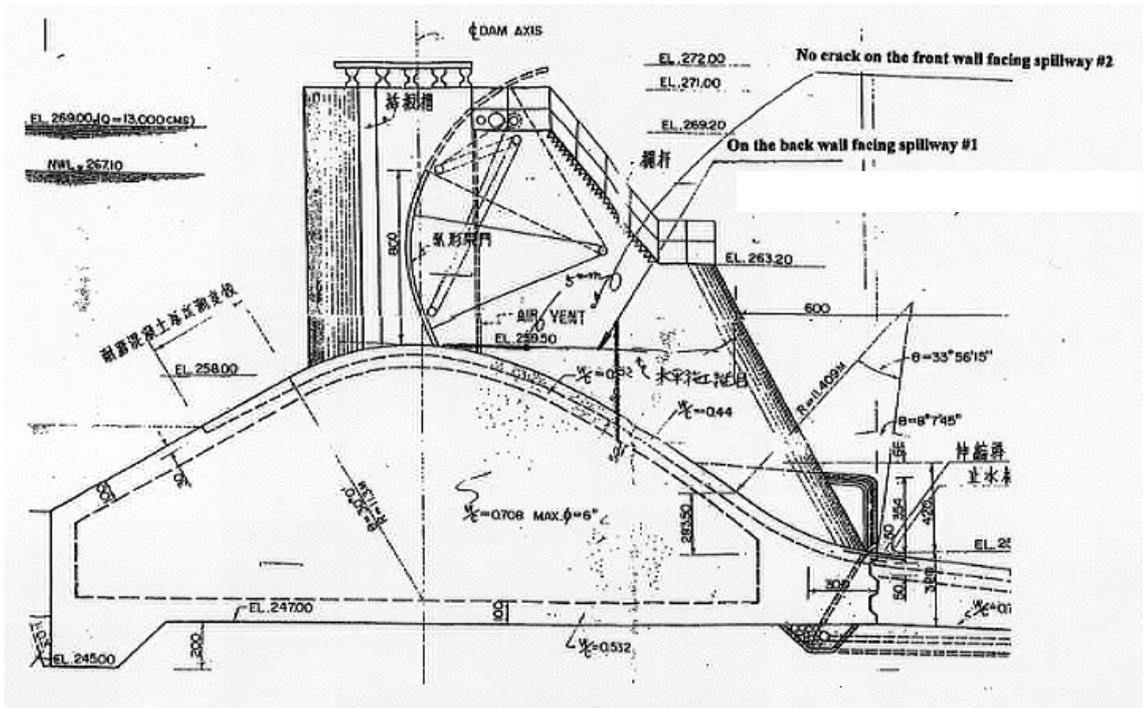


Figure 6.21 Cracks on Pier #3

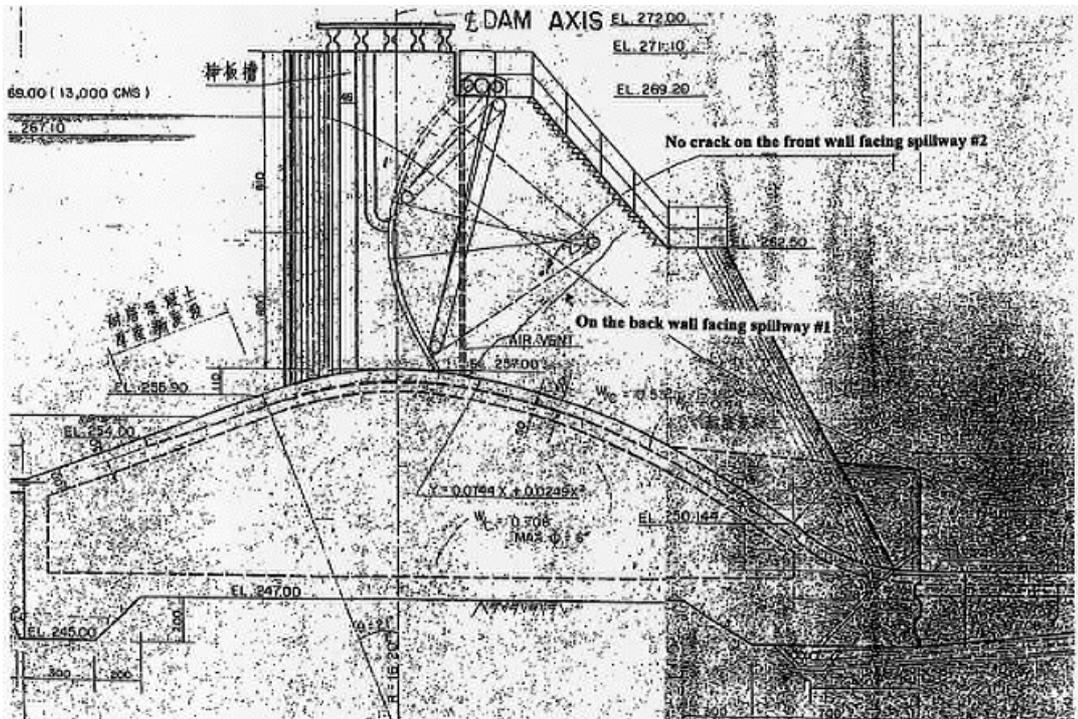


Figure 6.22 Cracks on Pier #1

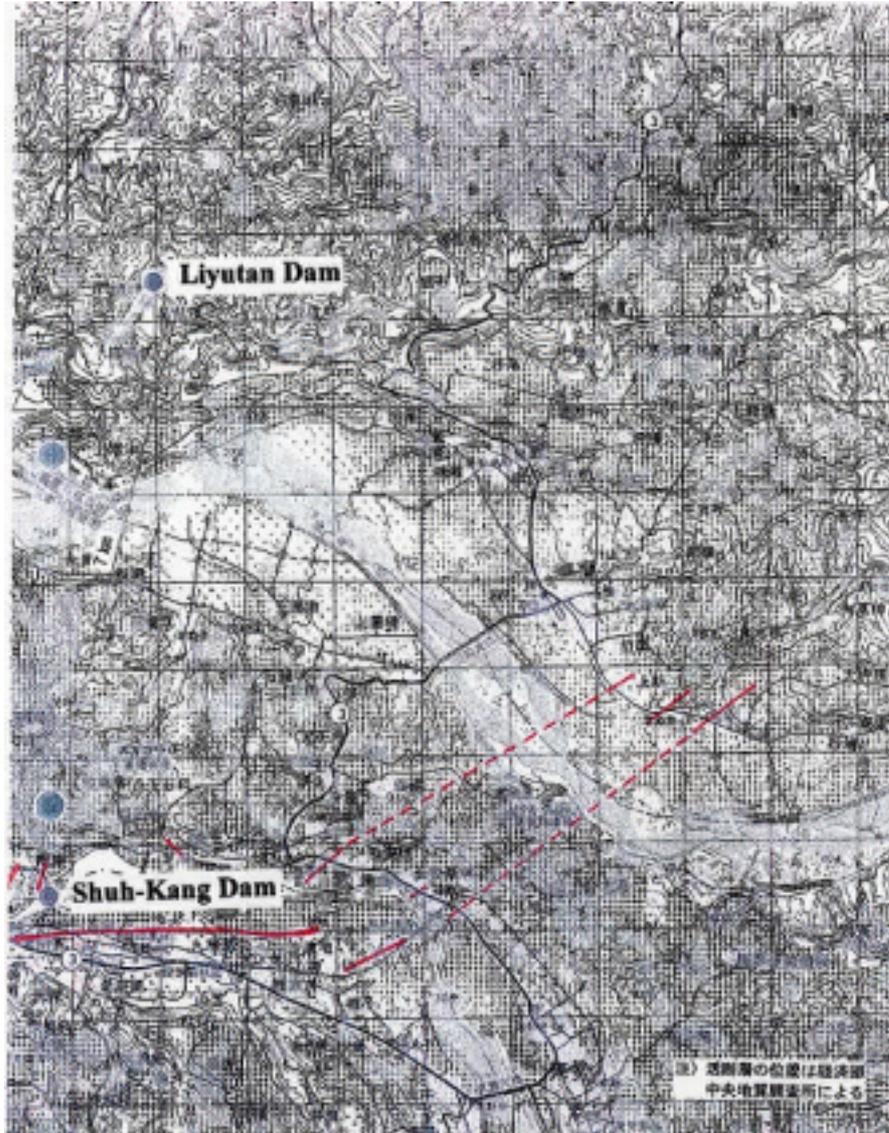


Figure 6.23 Liyutan Dam and Shih-Kang Dam

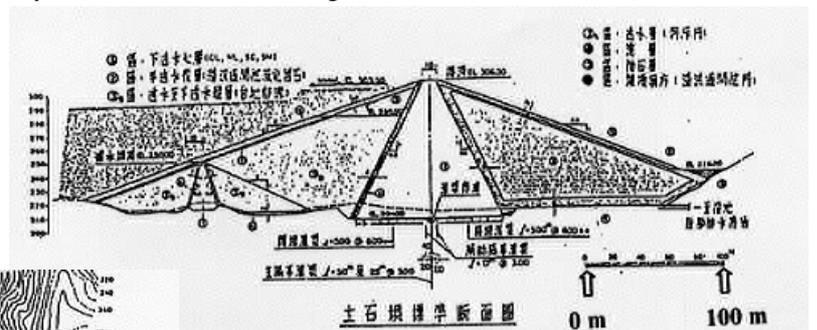


Figure 6.24 Plan of Liyutan Dam

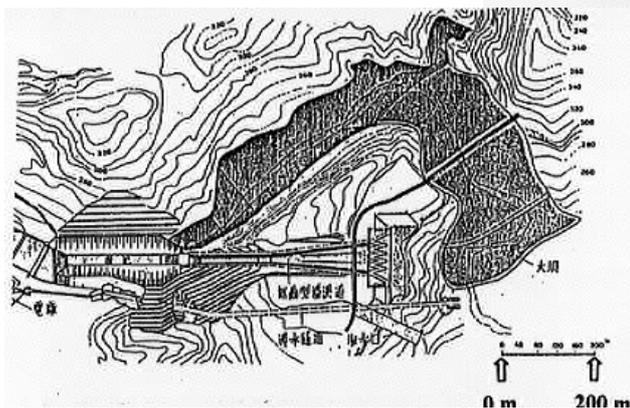


Figure 6.25 Transverse cross-section of Liyutan Dam

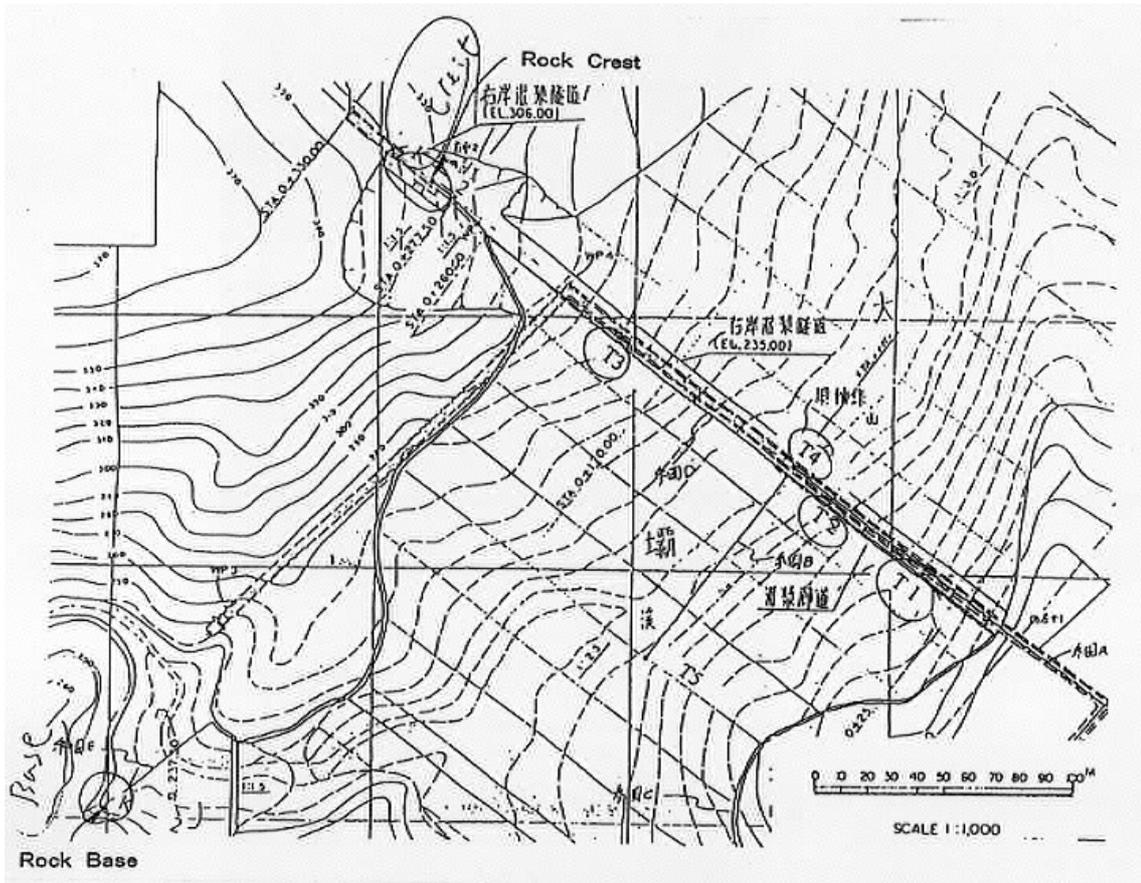


Figure 6.26 Arrangement of seismometers (Liyutan Dam)

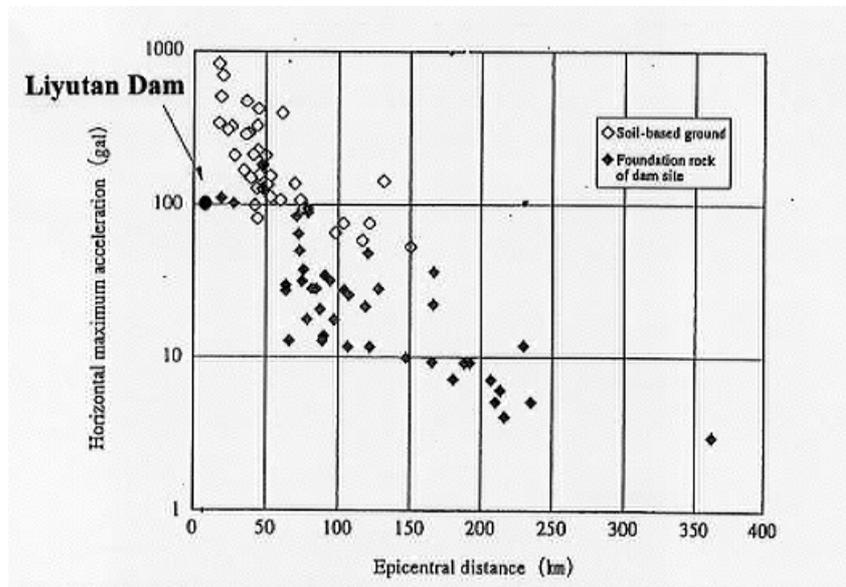


Figure 6.27 Peak horizontal accelerations on rock outcrops and soil deposits (Hyogoken-Nanbu Earthquake (Kobe Earthquake) of 1995)

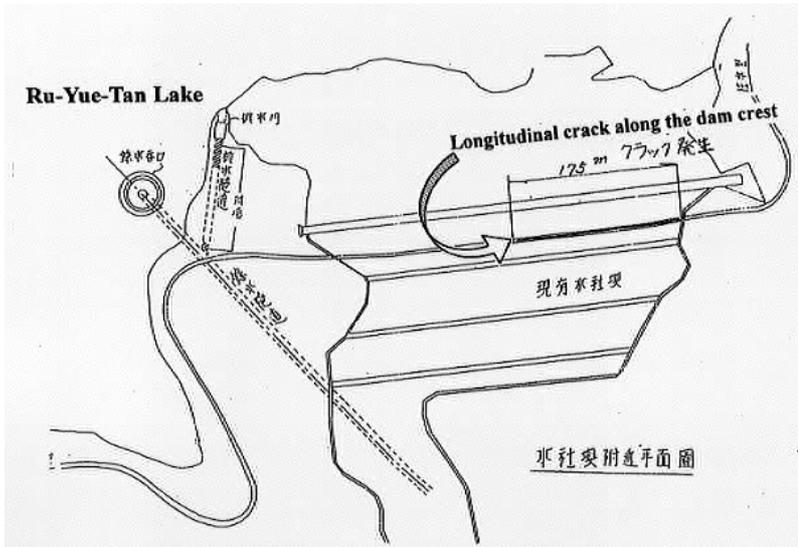


Figure 6.28 Plan of Suei-Sheh Dam

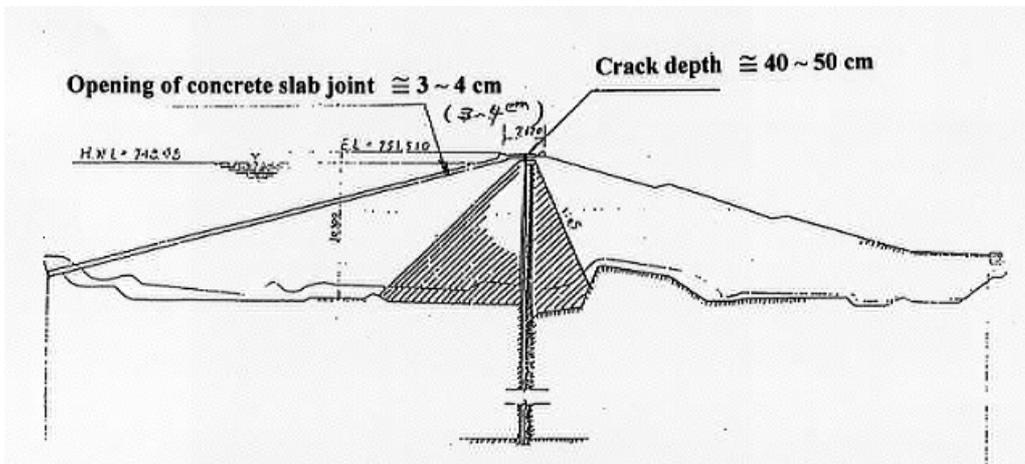
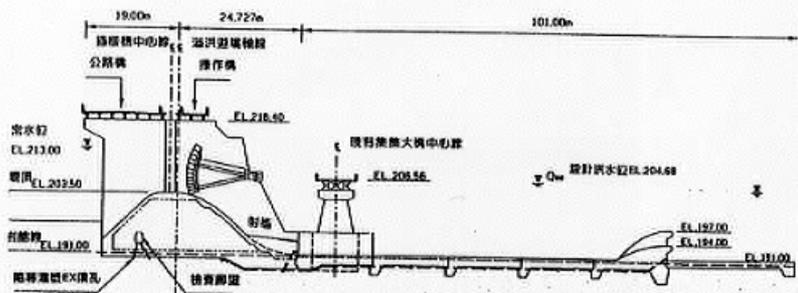
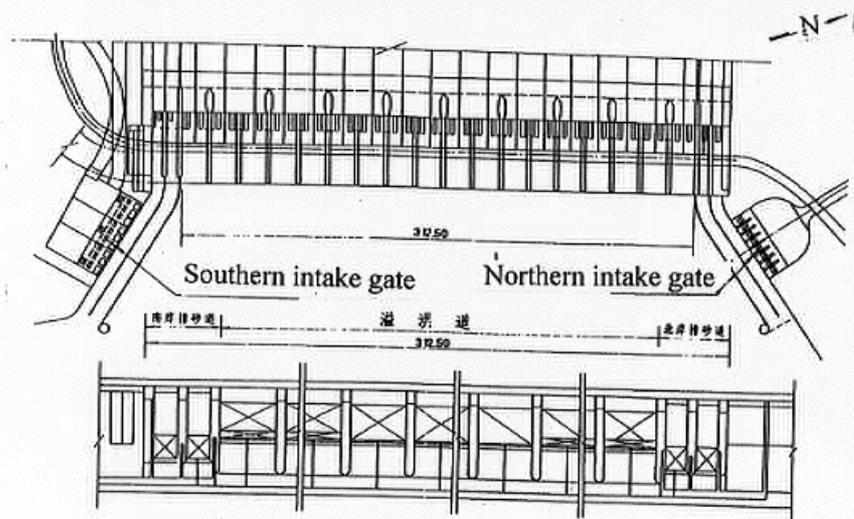


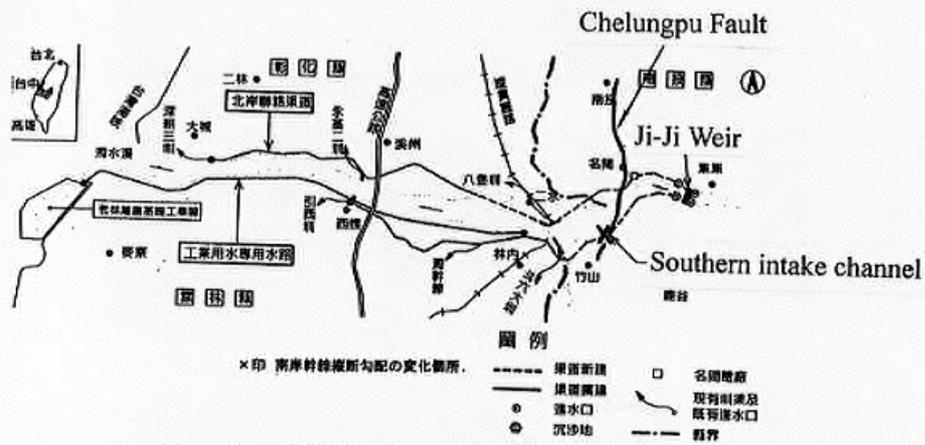
Figure 6.29 Transverse cross-section of Suei-Sheh Dam



Figure 6.30 Longitudinal crack along the crest of Suei-Sheh Dam



Plan, elevation, and transverse cross-section



Location of Ji-Ji Weir and Chelungpu Fault

Figure 6.31 Ji-Ji Weir