18 Debris Flow Control and Management: Case Studies from the Sichuan and Yunnan Provinces of China

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Debris flow hazards are quite common in the mountain areas of China. They often cause catastrophic destruction of infrastructure and personal property. Following 30 years' research and practical experience, debris flow control works have now been installed in many ravines. These have provided good economic, environmental, and social benefits.

This paper discusses two successful examples where the debris flow hazard to mountain roads and land has been reduced, the first in Heisha River, Xichang, Sichuan province and the second in Laogan Ravine, Dongchuan, Yunnan province, both in China. The debris flow control project along the Heisha River was successfully completed in 1978 with an investment of US$ 0.5 million. The Laogan Ravine project was completed in 1994 at a cost of US$ 0.17 million. There have been no debris flows in these ravines since the projects were completed.

These case studies show that measures to mitigate debris flow damage to linear infrastructures located in the deposition zone of debris flows should pay attention to controlling slope instabilities in the middle and upper reaches as well as to improving the environmental conditions in the catchment.

Introduction

Mountain areas cover two-thirds of China's land area. One-third of its population and about two-fifths of total cultivated land is found in these regions. The complex geological structure, intense ongoing tectonic and earthquake activities, and high monsoon precipitation make China one of the countries most susceptible to mountain hazards. Debris flows are one of the main types of hazard, and often have catastrophic consequences for mountain infrastructure and personal property. Due to their sudden occurrence, short duration, and strong destructive power, debris flows are a serious barrier to development and construction in mountain regions. There are more than 50,000 ravines in China's mountains that are prone to debris flows, and more than 8,500 of them pose severe risks to infrastructure.

Debris flow hazards are widespread over 31 provinces, autonomous regions, and municipalities. More than 900 counties and 150 cities, hundreds of factories and mine sites, 800 township sites, 36 railways, and half of all mountain highways are affected by debris flows. Every year, the direct economic losses due to debris flows amount to $US 18-25 million. Annually 250-500 people are killed and thousands injured. In addition, debris flows endanger farmlands, water conservation facilities, and rivers. Research on the origin of debris flows and hazard mitigation are of vital significance to China. Through over 30 years of research and practice, comprehensive mitigation measures have been successfully implemented in many ravines with serious debris flow problems. Debris flow control works along the Heisha River in Sichuan Province and the Laogan ravine in Yunnan Province (Figure 18.1) are two successful examples of using a multi-disciplinary integrated approach to mitigate hazards to mountain roads and farmland.

Case Study 1: Heisha River Debris Flow Control

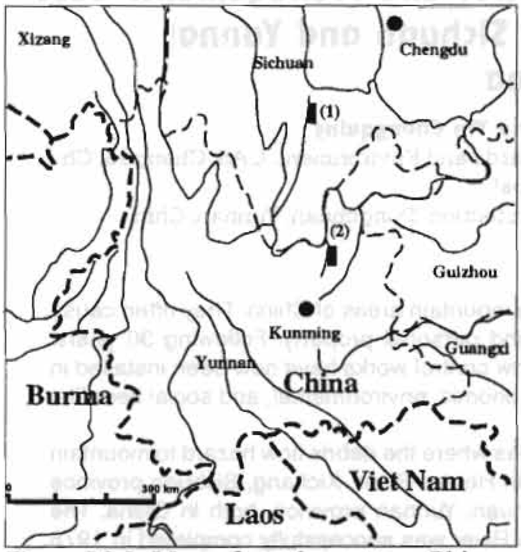

Figure 18.1: **Map of south-western China showing location of (1) the Heisha River watershed and (2) the Laogan ravine watershed**

The Heisha River in Xichang, southwest Sichuan, China is well known for its hazardous debris flow. The bare mountains, broken rock strata, and many landslides favour frequent debris flows. Between the 1950s and 1960s, five villages were destroyed one after another, 200 ha of cultivated land became wasteland, the Chengdu-Kunming Railway, and the Sichuan-Yunnan Western highway, and three main canals of Xichang city were seriously damaged. Twelve villages, one power plant, and more than 400 ha of cultivated land were threatened.

The Heisha River debris flow seriously threatened the Chengdu-Kunming Railway, which passed through its depositional fan. In 1967, to safeguard the railway and other infrastructures from debris flows, the Chinese Academy of Sciences organized a research team with members mainly from the Chengdu Institute of Mountain Hazards and Environment (IMHE). The team investigated and observed the Heisha River debris flow during 1967 and 1968. In 1970, in collaboration with ex-Xichang district and Xichang Railway Branch, the team made an integrated plan to control the Heisha River debris flow. In March 1971, the Government of Sichuan Province ratified the plan. The Chengdu IMHE was responsible for the technology while ex-Xichang district was responsible for construction and administration in cooperation with Liangsha Prefecture. The construction started in 1971 and was finished in 1978. Civil engineering works consisted of one flood-regulating reservoir, seven sediment-trapping dams, four check dams, seven division dams, a 5.8 km long division dyke and one flood-relief channel.

Bio-engineering works consisted of planting water-source holding forests over 800 ha, water and soil conservation forests on 400 ha, seven lines of debris flow preventing forests, and thirty-one windbreaks. Measures to improve farmland included terracing fields over more than 210 ha. Ex-Xichang County met the labour cost, and Sichuan Province Government invested US$ 0.5 million to implement the project.

Physical setting of the Heisha river catchment

The Heisha River is a tributary of the Anning River located about 28 km north of Xichang City. It originates from Lujihou Mountain in Xide County and joins with the Anning River at Lizhou Town, Xichang City. The river is located on the western slope of Daliangshan Mountain adjacent to southern Hengduan Mountain and the plateaus of Yunnan and Guizhou. The main stream is 12.6 km long and has a goldfish-like shaped catchment area of 22.7 sq.km. Geomorphologically it is stratified vertically and can be divided into the following four regions (Figure 18.2).

Lujihou Mountain — The mountain is the highest part of the catchment with an area of 5 sq.km. The highest point is at 2,920masl. The slopes are steep and there are two main ravines: the Ludong and Ongzu.

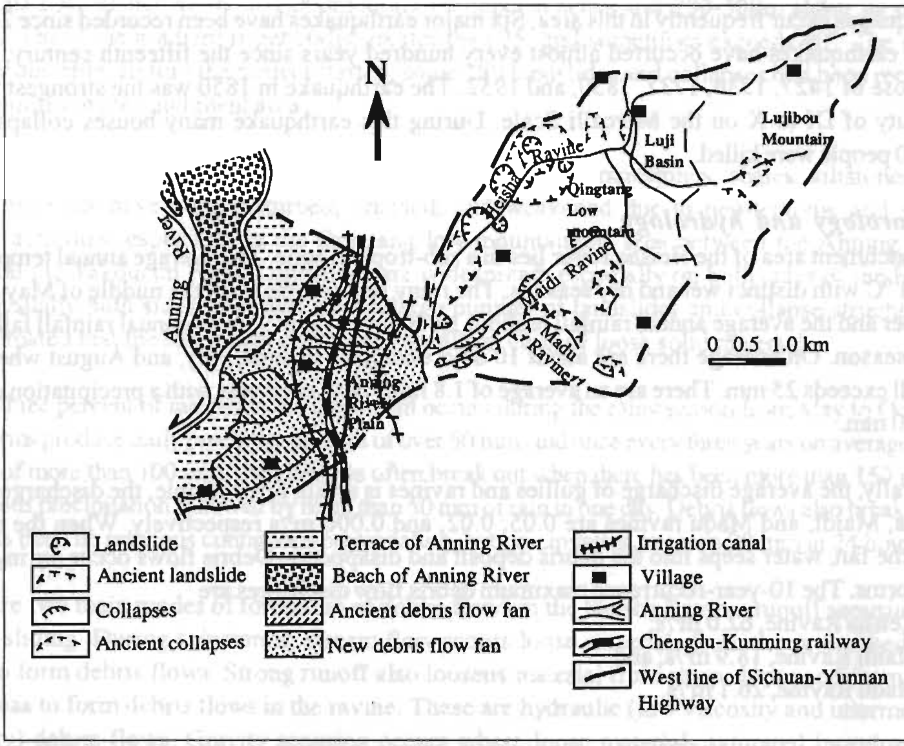

Figure 18.2: **Map of the Heisha River showing geomorphological characteristics and infrastructures lying on the fan**

Luji Basin — This is a fault bound basin lying in the middle of the Lujihou and Xitangli mountains. The basin is covered by alluvium deposited from the Ludong and Ongzu ravines. The basin covers 1.5 sq.km with altitudes ranging from 1,950 to 1,960m.

Qingtang Low Mountain — This includes the four ridges of Qinglongpo, Tangluopo, Hepupo, and Laripo with altitudes of 1,640 to 2,100m. The Heisha, Maidi, and Madu ravines lie between the ridges. The slopes are steep with a gradient of more than 25^0. There are many landslides and ravine erosions on both sides of the ridges that form debris flows. The area covered by this mountain is about 8.18 sq.km.

Anning River Plain and the Fan — The plain is about 3 km wide along the left bank of the Anning River and represents the lowest terrace of the river. The fan produced by the Heisha River debris flows lies above it. The fan covers an area of 5.33 sq.km, and has an average gradient of 2.0^0 and maximum elevation of 1,640m.

Tectonics and stratigraphy

The catchment is located in a major fault zone of the Anning River which passes through the Kang-Dian fold axis. The Anning River Fault and the Yakoucun Fault run through the catchment in a N-S direction. The former runs through the mountain pass under the Quaternary deposits and the latter runs along the southern fringes of Luji Basin. The Heisha Ravine anticline occurs on the west side of the fault.

Stratigraphically the catchment area is underlain by soft rock groups of Upper Triassic and Jurassic mudstone, siltsone, shale, and sandstone, as well as siltstone and sandstone with pebbles of the Lower Pleistocene, and young sediments from the Holocene.

Earthquakes occur frequently in this area. Six major earthquakes have been recorded since 208 AD. Large earthquakes have occurred almost every hundred years since the fifteenth century, including those of 1427, 1536, 1732, 1850, and 1952. The earthquake in 1850 was the strongest with an intensity of IX to X on the Mercalli Scale. During this earthquake many houses collapsed and 26,000 people were killed.

Meteorology and hydrology

The catchment area of the Heisha River lies in a sub-tropical zone. The average annual temperature is 17.1 °C with distinct wet and dry seasons. The rainy season runs from the middle of May to mid-October and the average annual rainfall is about 1,000 mm. About 93% of annual rainfall falls in the rainy season. On average there are about 10 days occurring in June, July, and August when daily rainfall exceeds 25 mm. There are an average of 1.8 rainy days each year with a precipitation of more than 50 mm.

Generally, the average discharge of gullies and ravines is small. For example, the discharges of the Heisha, Maidi, and Madu ravines are 0.05, 0.02, and 0.006 m^3/s respectively. When the streams enter the fan, water seeps into the debris deposit and disappears. Debris flows occur during heavy rainstorms. The 10-year-recurrence maximum debris flow discharges are

- Heisha Ravine, 62.0 m^3/s;
- Maidi Ravine, 18.9 m^3/s; and
- Madu Ravine, 26.1 m^3/s.

Where the Heisha River is joined by the above-mentioned ravines, the 10 year maximum discharge is 89.0 m^3/s. The debris flows travel downstream through the fan in seven branches which flow into the Anning River. The mainstream flow often changes its course between the seven branches.

Soil and vegetation

The catchment has acidic soil in the south-west mountainous area and the soil depth is mostly more than 1m. There are three sub-soil types in the catchment:

- mountainous red earth in the Qingtang low mountain area under 2,100m and in old fan deposits;
- mountainous red soil in the middle and lower part of Lujihou Mountain (above 2,100m); and
- mountainous yellowish-red soil in the upper part of the Lujihou mountain area. Brown, purple and black soils have developed in strongly eroded ravines and slopes.

Vegetation cover in the catchment is mainly composed of sub-tropical evergreen broadleaved trees and pines. The natural vegetation has been destroyed by human activities and only scattered shrubs and grasses remain. Forest cover was only 2.8% in the 1960s. A century ago, there were only a few inhabitants in the lower, middle, and upper reaches of the Heisha River and a dense forest grew in the catchment. Cultivated lands were few and far between. The ravine is narrow and debris flows occurred only rarely. With the coming of settlers, the population increased rapidly and forest cover was destroyed. Steep slopes of up to 35^0 were cultivated in the middle and upper reaches. Refuse from coal-mines was piled up everywhere. All these activities contributed to the development of frequent debris flows.

Formation of debris flows

The conditions which make the Heisha River catchment area prone to the formation of debris flows are summarised below.

The Heisha River lies at about 1,000m along its upper reaches and 200-300m along its middle reaches. The slope gradient is generally greater than 25° and sometimes exceeds 40°. The slopes are very unstable. Before the project started, some 180 landslides and collapses had been recorded in 135 gullies in the catchment area.

The lithology in the catchment is mostly soft rocks such as mudstones, shales, siltstones, and coal. The rocks have been disturbed, crushed, and weakened due to neo-tectonic and strong seismic activities, especially in the Qingtang low mountainous area between the Anning River Fault and the Yakoucun Fault. Landslides are widespread, especially on both sides of the Heisha River. Usually both sides of gullies have a large number of landslides and collapse structures. It was estimated that the catchment contained 26 million cu.m of loose solid material.

Ninety-three percent of rainfall in the catchment occurs during the rainy season from May to October. Rainstorms produce daily precipitation rates of over 50 mm, and once every three years on average daily rainfall of more than 100 mm. Debris flows often break out when there has been more than 150 mm of continuous precipitation followed by more than 50 mm of rain in one day. Debris flows also break when there has been no previous continuous precipitation, but precipitation exceeds 90 mm in 24 hours.

There are two main modes of formation of debris flows in the Heisha Ravine: runoff scouring and gravity sliding. During rainstorms, stream flow scours loose materials from the ravine beds and banks to form debris flows. Strong runoff also loosens material from steep slopes and from landslide areas to form debris flows in the ravine. These are hydraulic (low viscosity and intermediate viscosity) debris flows. Gravity scouring occurs where loose materials saturated by rainstorms have a decreased internal angle of friction. Earthslides move down the slope and enter the ravine to form debris flows. These are called sliding or viscous debris flows.

Debris flow processes in the mainstream of the river

The rainstorm runoff from the upper reaches of the Lujihou mountainous region collects in the Luji Basin, enters the middle reaches of the Heisha River where it scours loose deposits from the bed and banks, then receives additional debris flow from the sides, and finally forms a strong viscous debris flow in the mainstream of the Heisha River.

Various different types of rainstorm-triggered debris flows have occurred in the Heisha River catchment, but it is seen as a typical low viscosity type debris flow ravine. The average density of debris flows has been about 1.5 t/m^3. The Maidi Ravine has also had mainly low viscosity debris flows, although intermediate viscosity flows with densities of about 1.70 t/m^3 have also occurred. The Madu Ravine has had mainly low viscosity flows, but also occasional viscous debris flows with densities of 2.1 t/m^3. Low viscosity, intermediate viscosity, viscous, and plastic debris flows have occurred in small side branches.

The estimated peak discharge of the very large debris flow that occurred in 1874 was about 1,000 m^3/s. This flow damaged a four kilometre wide zone along its course. At Yuehua Village, debris deposits reached up to the eaves of houses. The 1964 debris flow had a discharge of 200 m^3/s. The largest debris flow in recent years was on June 30, 1971 with a peak discharge of 105 m^3/s (equal to the 10 year recurrence value). The peak discharge of the flow in Madu Ravine, on September 11 1972, was 36.5 m^3/s. If the reservoir had not been built in the upper reaches, the scale of debris flow would have exceeded that of 1964. The calculated peak discharge of a 100-year recurrence in Heisha River is 640 m^3/s.

The frequency of low viscosity debris flows is different to that of viscous debris flows. In some ravines there can be as many as100 viscous debris flows in a year, but low viscosity debris flows generally occur only once in several years or even decades. There are more than 20 viscous debris flows each year in the Majing Ravine. In the Heisha River, low viscosity debris flows occur once or twice a year. Hazardous debris flows, with a peak discharge of more than 100 m^3/s, occur about once every eight years and destructive debris flows about once every 50 years (as in 1874, 1927, and 1972). In 1972, the flow did not burst out in to the Heisha River mainstream because the reservoir had been built in the upper reaches.

The single largest quantity of solid materials carried down by a debris flow in this area was 0.308 million m^3 at Corfe at the confluence of the Heisha, Maidi, and Madu ravines. The average rate of deposition of debris in the fan is 5 cm/year with a maximum of 63 cm/year. More than 6m of debris flow deposits have accumulated since 1874 at the mouth of the ravine and more than 2m on the fan.

The area threatened by debris flow lies between Sankuaishi in the north and Guanzhangcun in the south. The maximum width of this area is 5 km over an area of 5.2 sq.km. There are seven radial branches of debris flows on the fan before they enter the Anning River. However, most debris flows end on farmland without reaching the Anning River. The mainstream keeps shifting. In 1958 it ran through Zhaojia Ravine but in 1968 it shifted to Miaokang Ravine.

Damage

The Heisha River debris flows are characterised by high discharge value, high-frequency, large volume of deposits, and channel shifting. These flows have caused repeated damage in the lower reaches.

Since 1874 debris flows have destroyed the five villages of Fujia, Maojia, Landiaofang, Aojia, and Zhangjia. The 1964 debris flow destroyed 74 houses. Over the past 100 years the Heisha debris flows have silted up more than 200 ha of cultivated land. The seven branches of the river on the fan often destroy the fertile fields located there. The flood used to submerge more than seven ha per year; one debris flow event in 1964 silted up and covered 74 ha of land.

Before 1970, the main irrigation canal of ex-Xichang county was blocked every year by debris flow sediments. In 1964, the canal was blocked in 13 places after one debris flow, preventing the irrigation of over 3,000 hectares of land. At present three canals cross the deposit fan in the lower reaches of the Heisha River.

One of the main power plants of ex-Xichang district, the Yuehua Power Plant, is located in the middle of the No. 2 and No. 3 branches of the seven channels. Debris flows have blocked canal inflows many times interrupting electricity generation. There is only 100m distance between No. 2 branch and the generator room so that a large-scale debris flow could destroy the factory houses and engines.

In the 1960s, the Sichuan-Yunnan highway was often damaged during the rainy season and its alignment had to be shifted. Vehicles were carried away by the debris flows. One debris flow destroyed a 1.5 km long road in 1964, and in 1968 a moving car was buried. The section of highway in the lower reaches of the Heisha River is one of the most frequently damaged sections on the Sichuan-Yunnan highway.

Whilst selecting the alignment of the Chengdu-Kunming railway, the Heisha River section was regarded as the most hazardous crossing. To safeguard the railway, seven bridges were built over the seven branches of the Heisha River. Although the railway project involved a large investment little consideration was given to protecting the railway from debris flows. The railway was damaged twice during its first year of operation in 1965. The first large-scale damage occurred on September 18, 1970. The pier protection of one of the bridges was destroyed following a peak discharge of 170 m^3/s after intense rainfall (34 mm in an hour). The second heavy damage was on June 30 1971. This time the railway was destroyed at three places by low viscosity debris flows with peak discharges of 105 m^3/s. Some houses in Miaokan Village were submerged.

Because of the concentration of debris flows at the bridge openings, the potential for disaster in the lower reaches actually increased. The construction of the seven bridges increased the damage to farmland in the lower reaches and did not protect the railway from debris flow hazards. The only way to safeguard the railway and agricultural land was to implement integrated measures to control the Heisha River debris flows.

Integrated control measures

An integrated plan for debris flow control was drawn up that took into consideration both the debris flow characteristics of the Heisha River and other successful examples of debris flow control at home and abroad. Bioengineering and civil engineering measures were combined with comprehensive planning for the upper, middle, and lower reaches and an integrated management plan for mountain, river, forest, and farmland. The integrated measures consisted of

- planting water-holding forests in the clear-water areas of the upper reaches;
- building a flood-regulating reservoir to regulate water discharge;
- planting water and soil-conservation forests in the farm areas of the middle reaches and building sediment-trapping dams, check dams, and protection dykes to stabilise slopes and fix ravine beds to control debris flow formation; and
- building diversion dykes, excavating flood-refill channels, and planting protection forests in the deposit area to fix the ravine bed.

Bio-engineering

The bio-engineering measures used are summarised in Table 18.1.

Water-holding forests of *Pinus yunnanensis*, *Cyclobalanopsis glauca* and other tree species were planted on more than 667 ha of Lujihou Mountain, Luji Basin, and the surrounding areas.

Water and soil conservation forests, using trees, bushes, and grasses were planted in the low mountain areas of Qingtang, where debris flows originate. The trees included *Pinus yunnanensis*, *Pinus khasya*, *Pinus armandii*, *Quercus glauca*, *Alnus cremastogyne*, and *Robinia pseudoacacia;* bushes like *Coriaria sinica* were planted in areas with poor soil and poor growing conditions. Grasses like *Themeda triandra var. japonica* were planted and protected in the areas with the most hostile growing conditions.

Dyke-protection and windbreak forest belts were planted in the debris flow deposit areas in the lower reaches and around settlements. A 15m wide, 1.5 km long plantation was established in the dyke-protection belt. *Robinia pseudoacacia* was the main species planted, other species included *Alnus cremastogyne*. A 10-20m wide windbreak belt of trees, mainly *Robinia pseudoacacia, Eucalyptus robusta, Paulownia fortunei*, and *Ligustrum fragrans,* was planted on the former fan deposit running parallel to the diversion flume of the Heisha River.

Table 18.1: **Bio-engineering measures used in the Heisha River catchment**

Afforestation zones		Plantation types		Soil types	Soil-vegetation types	Afforestation methods
Zone	Sub-zone					
Mountainous area	Middle hills	Soil and water conservation	Water source protection	Red soil and yellow-red soil	Medium-deep soil with humid shrubs	Air-seeding sowing by hand, spreading, sowing by dibbling
	Gentle slopes		Watershed protection	Red soil and red earth	Deep soil with humid grass	
	Steep slopes		Sloping land protection	Purple soil, purple-brown soil	Medium-deep soil with less humid grass	Same as above and afforestation by planting saplings
	Collapses and landslides		Protecting collapses and landslide	Black young stage soil	Landslides and ravines with thin, exposed soils	
	Upper part of ravine		Regulating water flow	Purple-red-brown soil		
	Bottom of ravine		Controlling ravine-bottom erosion	Recent stone and sand layers		
	Exposed land		Controlling exposed land erosion			
Plains	Debris flow deposit fans	Checking wind	Protecting a dam against debris flow	Stony soil in floodland and sandy soil		
	Cultivated land	Protecting channels and fields	Protecting channels and cultivated fields	Rice soil	Deep soil with humid agricultural zone	

Economic trees (i.e., nut, fruit, or other trees grown for cash crops) were planted on previously cultivated land that had been laid waste by debris flows. The main trees planted were *Malus* and *Alba*, with subordinate species including *Malus pumila* and *Pyrus* spp. The total area of these forests was about 66 ha. The area has developed into an important centre in Sichuan Province for the production of silkworm cocoons.

Civil engineering

The civil engineering works used for debris flow control are summarised in Table 18.2.

A 23m high reservoir, the Qiyi reservoir, was built at the exit of the Luji Basin (Figures 18.3 and 18.4). The reservoir has a storage capacity of 656,000 m^3 and collects water from from a 9.2 sq.km catchment area, 72% of the total Heisha Ravine catchment. During the rainy season the reservoir acts as a flood regulator. The 20-year-frequency flood peak discharge of 64.6 m^3/s and 100-year-frequency of 110 m^3/s can be reduced to 13.4 m^3/s and 33.9 m^3/s respectively when a storage capacity of 601,000 m^3 is used to regulate annual floods and hold the water (Table 18.3). Since the completion of the reservoir in 1972, the mainstream of the Heisha Ravine has not produced any substantial debris flows and neither has the Heisha River. The reservoir dam was made of earth using hammer-ball installation. This type of construction can easily be manipulated to drain sediment away. In the event of a 100-year-frequency flood, if in-reservoir discharge is 1 m^3/s, the water level can be reduced to the normal level of 10.2m within 48 hours. Even in the highly unlikely event that a rainstorm of the same strength occurred the next day, the reservoir would still be safe.

Sediment-trapping dams are mainly used to arrest the earth in debris flows. Seven sediment-trapping dams were constructed. No. 1 was designed to arrest sediment, stabilise landslides, and prevent down-cutting; No. 5 was designed to stabilise landslides; and No. 7 was designed to raise the erosion base. The dams were all cement masonry gravity dams or cement masonry gravity arch dams (Figure 18.5). The dimensions of the dams are shown in Table 18.3. Various foundation structures

Figure 18.3: **The flood regulating Qiyi reservoir constructed in the Luji Basin, in the upper reaches of the Heisha Ravine**

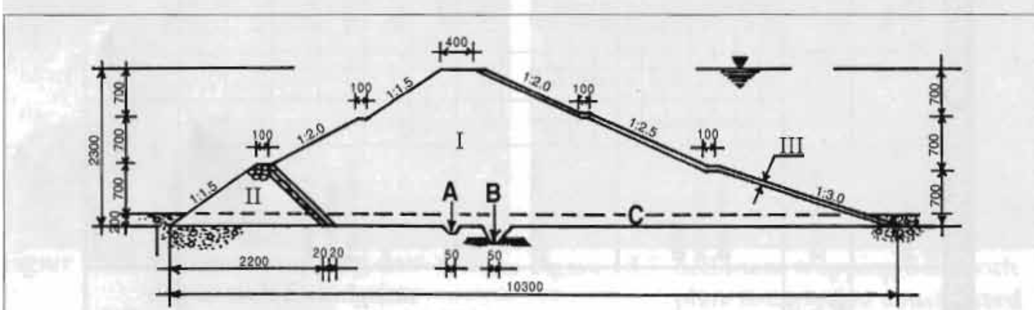

Figure 18.4: **Section through the earth dam of Qiyi Reservoir, I - earth dam; II - water-filter dam; III - slope protection; A - centre groove; B - catch drain; C - old ravine bed**

Table 18.2: **Civil engineering works for debris flow control of the Heisha River**

Engineering location	Engineering project	Symbol		Engineering dimension: Length (m)	Height (m)	Width of top (m)	Width of bottom (m)	Length of spillway (m)	Height of spillway (m)	Width of spillway (m)	Depth of foundation (m)	Gradient of front side	Gradient of back side	Standard: Design (p)	Check (p)	Engineering structures
Flood regulating engineering in upper reaches	X-Reservoir			106.6	22.0	4.0	96.0	6.0	17.0	4.0	1.0-2.0	1:2-1:3	1:1.5-1:2	1	0.1	Earth dam with mortar masonry spillway
Small-scale engineering	Sediment-trapping dams	1	A1	70.7	7.1	1.0	7.0	20.0	5.0	20	45	1:0.3-1:0.4	1:0.2	2	0.5	Mortar masonry gravity dam
		2	A2	45.7	5.5	0.7	4.3	16.0	3.5	1.6	3.1	1:0.3-1:0.4	1:0.2	2	0.5	Mortar masonry gravity dam
		3	A3	42.5	5.6	0.8	4.0	10.0	3.5	1.5	3.0	1:0.3-1:0.4	1:0.2	2	0.5	Mortar masonry arch dam
		4	A4	51.6	6.0	0.8	6.2	14.0	4.0	2.0	1.0	1:0.4	1:0.2	2	0.5	Mortar masonry gravity dam
		5	A5	47.0	6.0	1.0	5.8	14.0	4.0	2.0	4.0	1:0.3-1:0.4	1:0.2	2	0.5	Mortar masonry gravity dam
		6	A6	43.5	12.0	1.0	9.2	7.0	9.0	2.5	1.2	1:0.3-1:0.4	1:0.2	2	0.5	Mortar masonry gravity dam
		7	A7	24.0	5.2	0.8	4.3	10.0	3.0	2.0	1.0	1:0.6	1:0.0	2	0.5	Mortar masonry gravity dam
	Check dams	1	B1	11.9	6.0	1.0	4.9	2.0	4.0	2.0	1.0	1:0.3-1:0.4	1:0.2	5	2	Mortar masonry gravity dam
		2	B2	16.1	6.0	1.0	3.6	4.0	4.0	5.0	1.0	1:0.3-1:0.4	1:0.2	5	2	Mortar masonry gravity dam
		3	B3	13.6	6.5	1.0	4.2	3.0	4.5	1.6	1.5	1:0.3-1:0.4	1:0.2	5	2	Mortar masonry gravity dam
		4	B4	12.4	3.5	1.0	1.5	3.0	1.5	1.0	0.3	1:0.0	1:0.0	5	2	Reinforced concrete box-like sub dam
		5	B5	15.5	6.4	1.0	2.5	3.0	4.4	1.5	1.0	1:0.0	1:0.0	5	2	Reinforced concrete box-like main dam
	Longitudinal dyke and revetment	1	C1	70.0	2.0	0.8	1.5-2.5				1.5-2.0			5	2	Mortar masonry dam or revetment
		2	C2	32.0	2.0	0.8	1.5-2.5				1.5-2.0			5	2	Mortar masonry dam or revetment
		3	C3	20.0	2.0	0.8	1.5-2.5				1.5-2.0			5	2	Mortar masonry dam or revetment
		4	C4	14.0	2.0	0.8	1.5-2.5				1.5-2.0			5	2	Mortar masonry dam or revetment
		5	C5	41.0	2.0	0.8	1.5-2.5				1.5-1.2			5	2	Mortar masonry dam or revetment
		6	C6	25.0	2.0	0.8	1.5				2.0	1:0.5	1:0.0	5	2	Mortar masonry dyke
		7	C7	10.0	2.0	0.8	2.0				1.5	1:0.5	1:0.2	10	2	Mortar masonry dyke
Diversion engineering in lower reaches	Diversion dyke			5800	2.0-2.6	2.0	6.5-8.5				1.0-1.2	1:1.0	1:1.5	5	2	Earth dyke with mortar masonry
	Diversion weir			28.0	1.0			28.0	1.0	15.0	1.7					Mortar masonry
	Drainage canal			1500	1.6-2.0	6.5	4-5									Excavation

Table 18.3: **Peak discharge in and out of the Qiyi reservoir calculated for different rainstorm-frequencies**

Frequency for design (p%)	Relative water level (m)	Peak discharge in into reservoir (m^3/s)	Peak discharge from reservoir m^3/s	Cutting discharge m^3/s
0.1	20.5	181	65.0	116
0.2	20.1	162	54.5	108
0.5	19.6	132	43.9	88.1
1	19.1	110	33.9	76.1
2	18.7	91.2	26.0	65.2
5	17.9	64.4	13.4	51.2

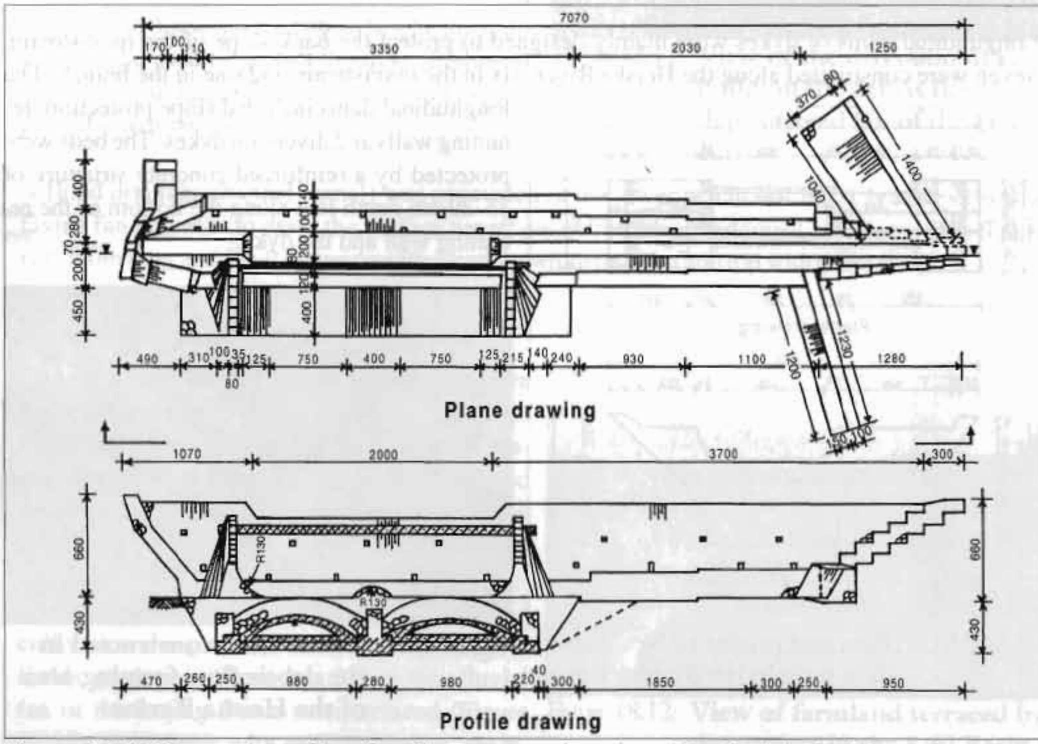

Figure 18.5: **Plan and profile of sediment trapping dam No. 5 with double arch foundation**

Figure 18.6: **Sediment trapping dam with single-arch foundation constructed across the main stream of the Heisha Ravine**

Figure 18.7: **Sediment trapping dam with plate foundation constructed in the landslide area of the mainstream of the Heisha Ravine**

and auxiliary dams were installed to prevent failure due to foundation scouring. Double arches (Figure 18.5), single arches (Figure 18.6), and wedges were used to for the main dam foundations. Arch, beam, plate, and gravity structures were used in the design of the auxiliary dams (Figures 18.6 and 18.7); of these only the gravity type is used regularly outside of China.

Check dams are low volume sediment-trapping dams built in gullies. Five check dams were built; typical plan and profile diagrams are shown in Figure 18.8 (No. 2 check dam built in the middle reach of the Majing Ravine). Figure 18.9 shows a series of check dams built in the debris flow forming area of the Heisha Ravine.

Longitudinal dams or dykes were mainly designed to protect the bank slope of the mainstream. Seven were constructed along the Heisha River: six in the mainstream and one in the branch. The longitudinal dams included slope protection, retaining walls and diversion dykes. The beds were protected by a reinforced concrete structure of 15-20 cm depth laid along the bottom of the retaining wall and the dyke.

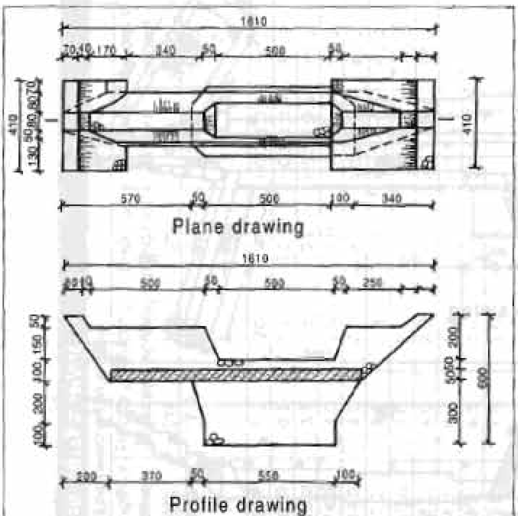

Figure 18.8: **Plan and profile of No. 2 check dam built in the Majing Ravine**

Figure 18.9: **Check dams constructed in the debris flow forming area of the Heisha Ravine**

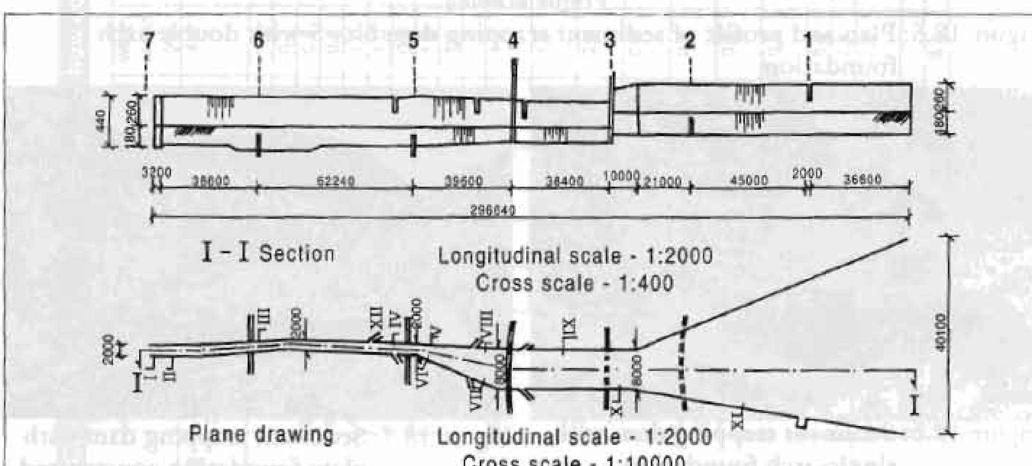

Figure 18.10: **Cross-section of Heisha River diversion flume**
1. Diversion; 2. Lugu canal; 3. Sichuan-Yunnan highway; 4. Chengdu-Kunming railway; 5. Xili canal; 6. Lianghe canal; 7. Anning River

The diversion flume built in the lower reaches of the Heisha River was 2.9 km long. A 2.5 m high diversion dyke was built on both sides of the river (i.e., total length of dyke 5.8 km). The plan of the dyke is shown in Figure 18.10 and the completed dyke in Figure 18.11. Most of the dyke is earthen with the surface protected by cement masonry. There is a spillway in the upper section of the diversion dyke. When debris flows or flood levels in the flume reach a critical height, the spillway can be used to protect the dyke. Sediment exits in the middle and lower reaches are used to push the sediment away.


Figure 18.11: **View of the diversion dyke build on the debris flow depositional fan of the Heisha Ravine**

A flood drainage channel (canal) was excavated in the lower reaches of No. 1 branch - Huoshao ravine fan deposit - to drain the surface runoff away from the fan deposit and slope. The channel is 1,500m long and 1.6-2.0m wide with a bottom width of 4-5m and top width of 6.5m.

Improving agriculture

One very important intervention was to improve the stability and reduce erosion rates in surrounding areas by changing the land use pattern. General erosion was reduced by replacing cultivated areas on steep slopes with forests. Cultivation was forbidden on slopes exceeding 25^0 and forests were planted in the middle and upper catchments. Fields were terraced, and strip field and cultivation along contour lines was encouraged. Fields on slopes of less than 25^0 on the alluvial fan of the Lujing Basin were terraced (Figure 18.12). Strip fields with straight ditches, roads, and trees were built on the old fan outside the diversion flume.


Figure 18.12: **View of farmland terraced by the project in the Luji Basin in the upper reaches of the Heisha River**

By 1978, the forest covered 680 ha, 62% of the mountainous area of the middle and upper parts of the Heisha River catchment. Thirty-nine rows of trees had been established in the lower reaches and 1,700,000 trees had been planted around houses. Thirty-one hectares of t mulberry were established. These have since been added to and mulberry trees now cover 63 ha. Figure 18.13 shows a plan of some of the civil engineering works and land use patterns.

Summary

The project was completed in 1978 with an investment of US$ 0.5 million. Since its completion, there has been no debris flow in the mainstream of the Heisha River. With the measures taken, the catchment should be able to withstand the type of rainstorm that occurs once every 50 years. The sediment carried from the upper reaches is now less than a quarter of what it was were before the project started. The flood peak discharge induced by a 10-year recurrent rainstorm is only a fifth of what it was before the project. The peak flood discharge of the mainstream is only a twentieth of

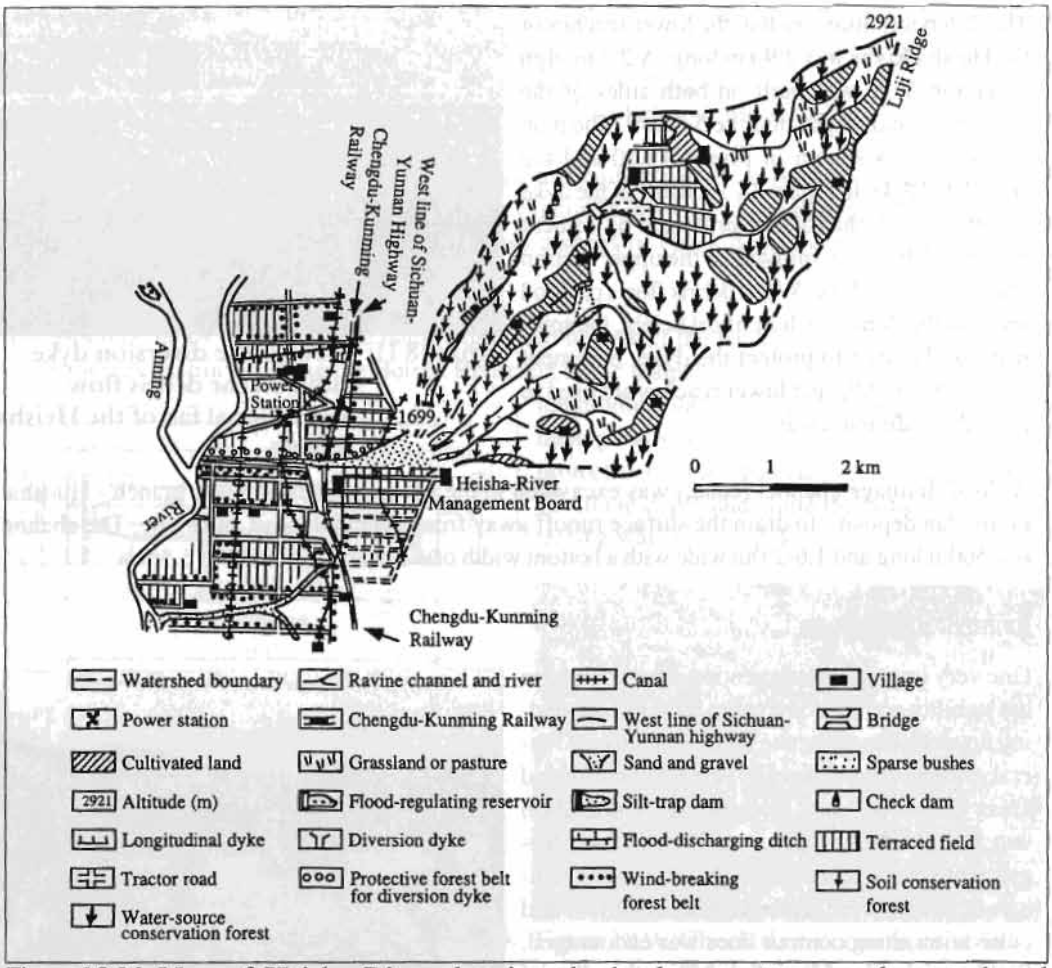

Figure 18.13: **Map of Heisha River showing the land use patterns and control and engineering structures**

what is was in the year the project started. This project has not only mitigated debris flow hazards and protected the railway, highway, power station, villages and farmland, but has also reclaimed 130 ha of farmland, increased the irrigated area by 75 ha, and substantially raised crop yields. Since the completion of the project, a silkworm mulberry farm has been set up on the debris flow fan with an annual production in excess of US$ 1.23 million yielding a net profit of US$ 123,000 to the community. This is impressive when compared to the total investment for the project.

Case Study 2: Debris Flow Control in Laogan Ravine

Laogan Ravine is located 11 km south of Dongchuan city, in Yunnan province, China (Figure 18.1), and is a tributary situated in the middle reaches of the Xiaojiang River. The Xiaojiang River is a tributary of the upper Yangtze River. The catchment area of the Laogan Ravine is 7.7 sq.km and the altitude ranges from 1,300m to 2,600m. The main stream is 5.7 km long with gradients ranging from 10 to 14°. The villages of Zhiga, Heishan, Xiaoxincun, and Xiaomaidi lie in the catchment area. From the 1960s to the 1980s, debris flows from the Laogan Ravine endangered the railway and highway linking Dongchuan and Kunming. A large irrigation canal constructed on the fan deposit of the Laogan Ravine was also threatened. The main features of the area are shown in Figure 18.14.

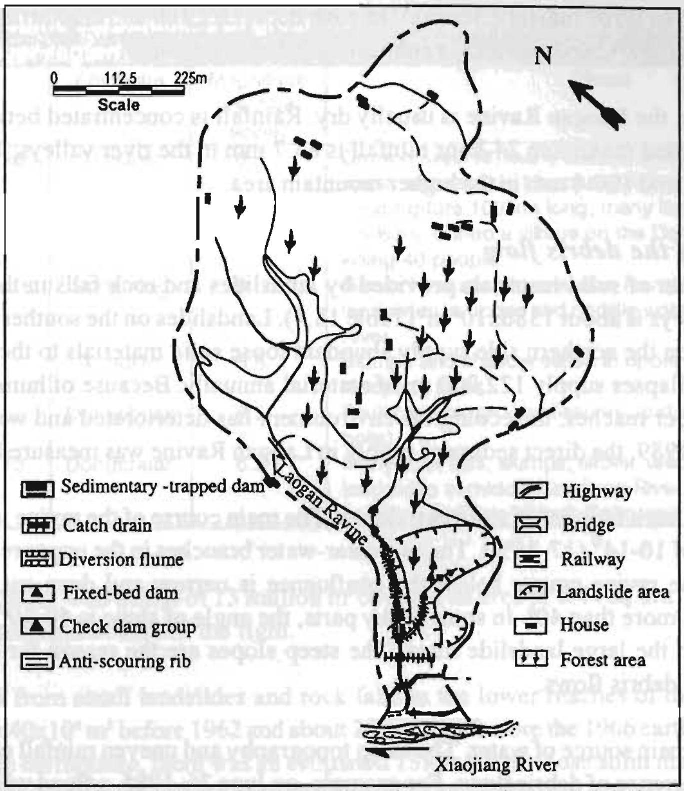

Figure 18.14: Map of Laogan Ravine showing landslides, infrastructure and control measures

Physical setting

The Xiaojiang River catchment is located on the east fringe of the Kang-Dian Axis and on the western fault line of the 'Kunming Hollow'. The project area belongs to the major fault belt of the Xiaojiang River. The north-north-west trending Laogan Ravine Fault runs through the catchment. Tectonic movement causes landslides and collapses along the Xiaojiang River fault belt.

The Laogan Ravine is located in the east of the middle section of the large Xiaojiang Fault. Above an altitude of 1,900m, the outcrops of bedrock are mainly dolomite limestone of Devonian, Carboniferous, and lower Permian age. Below 1,900m, highly-weathered Emeishan basalts of Permian age occur. The outcropping of bedrocks is small as most of the catchment area is covered by landslide and collapse deposits. Semi-weathered basalt can be seen in the middle and lower parts of the mainstream.

The Laogan Ravine catchment has an oak leaf-like topography with very steep slopes below 1,900m. The steep terrain has many deep ravines and gullies. Rapid runoff from the steep slopes is the main contributor to surface solid materials and debris flows.

Meteorology and hydrology

The climatic conditions range from semi-dry to wet-tropical. Below 1,300m, there is a semi-dry river-valley zone with temperatures ranging from 20° to 40°C. The average annual rainfall is 800 mm. The zone between 1,600 and 2,100m has an average temperature of 17.5°C and average rainfall of 900 mm (at 1,600m) to 1,707 mm (at 2,100m). The zone between 2,100 and 2,600m has a mean minimum temperature of -8.32°C and an average annual rainfall of 1,040 mm.

Hydrologically, the Laogan Ravine is usually dry. Rainfall is concentrated between June and August. The recorded maximum 24-hour rainfall is 83.7 mm in the river valleys; 117.2 mm in lower mountain area; and 100.4 mm in the higher mountain area.

Formation of the debris flow

The total amount of solid materials provided by landslides and rock falls in the ravine estimated from field surveys is about 1386x10^4 m^3 (Table 18.4). Landslides on the southern side of the ravine and rock falls on the northern side supply abundant loose solid materials to the debris flow. Bank erosion and collapses supply 122,000 m^3 of material annually. Because of human activities in the middle and upper reaches, the ecological environment has deteriorated and water and soil loss is worsening. In 1989, the direct sediment supply in Laogan Ravine was measured as 150,000 m^3.

The catchment has a high relief and steep slopes. The main course of the ravine is 5.7 km long, with bed gradients of 10-14° (17-25%). The two clear-water branches in the upper reaches join with the mainstream; the ravine course below the confluence is narrow and deep-cut. The slope of the ravine banks is more than 40°. In some rocky parts, the angle of slope is 40-50°. There are several small gullies in the large landslide mass. The steep slopes are the reason for the strong erosion capacity of the debris flows.

Rainfall is the main source of water. The steep topography and uneven rainfall over time and space favour the occurrence of debris flows. For example, on June 26, 1985, a flood with a discharge of 30 m^3/s eroded the landslide mass on the left bank setting loose solid materials to form a viscous debris flow with a discharge of 91.5 m^3/s and velocity of 6.5 m/s. This one-time deposit amounted to 145,000 m^3.

Human activities have contributed to debris flow formation. Studies have shown that the vegetation cover in the Laogan Ravine catchment area was 40% before 1949. The collapsed mass in the ravine remained stable before railway and road building began in 1956. The canal constructed in 1958 ran through the upper parts of an old landslide which was reactivated by the seepage from the canal. Increasing population levels led to the cutting down of trees and cultivation on the steep slopes.

The recorded earthquakes of higher magnitude and their effects in the Xiaojiang River catchment area are summarised in Table 18.5. The strong earthquake of February 5, 1966 at Xiniu Mountain in Dongchuan close to the Laogan Ravine, reactivated a huge landslide in the lower catchment of the

Table: 18.4: Volume of materials estimated from landslides in the upper reaches of Laogan Ravine in 1989

	Type	Area (km$_2$)	Avg. width (m)	Avg. slope (°)	Coefficient of slope	Avg depth (m)	Storage (x10$_4$ m$_3$)	Note
South of main stream	Landslide	0.444	450	25	0.065	29.3	1302	
North of main stream	Collapse	0.0612	108	36.5	0.126	83.3	83.3	
Upper and middle reaches	Surface & groove erosion	7.1984					2.8	Medium level of erosion assumed
Total							1386.3	

Table 18.5: **Historic earthquakes of great magnitude and their effects in the Xiaojiang River region**

	Epicentre	Magnitude (Richter scale)	Effects
1713, February 26	Xundian	6.5	Ground fissures, many slumps and shallow slides in upper watershed of Xiaojiang river
1733, August 2	Dongchuan	6.75	Fault rupture 100 km long, many landslides, one large landslide buried a village on the Daqiao tributary killing 40 people.
1833, September 6	Songming	8	Ground fissures, liquefaction (sand boils), many landslides in upper and middle watershed of Xiaojiang River
1927, March 15	Xundian	5.5	Slumps and shallow slides in upper watershed of Xiaojiang River
1966, February 5	Dongchuan	6.5	Fault rupture, ground fissures, and liquefaction (sand boils)
1966, February 13	Dongchuan	6.2	Many rock falls, slumps, slides; reactivated ancient landslides in middle Xiaojiang River watershed; combined effects of both February, 1966 earthquakes

ravine. The landslide with debris of 13 million m^3 covered an area of 0.44 sq.km. The mass that slid pushed the mainstream course to the right.

The total debris from small landslides and rock falls in the lower reaches of the ravine was estimated to be only $40x10^4$ m^3 before 1962 and about $200x10^4$ m^3 before the 1966 earthquake. By the end of 1989, after the earthquake, there was an estimated $1386x10^4$ m^3 loose solid material and the area of the landslide had increased to 0.5 sq.km from 0.27 sq.km in 1963.

Characteristics of the debris flow

The Laogan Ravine debris flow is turbulent. The density of the debris mass is 1.4 to 1.8 t/$m^3$and the discharge takes place in a single peak. The flows have caused bank undercutting and slope failure. The Dongchuan Institute of Debris Flow Protection and Investigation measured a peak discharge of 91.5 m^3/s and a velocity of 6.5 m/s on June 26, 1985.

Two very large-scale debris flows that occurred in 1985 and 1987 deposited more than 10m of debris and scoured more than 3m out of the main ravine course above the highway. The most recorded material deposited by one flow was 145,000 m^3. The ravine was formerly 250m long and 8-10m wide in the lower reaches. After the June 1985 debris flow, the width of the ravine increased to 30-50m. Figure 18.15 shows the particle sizes of the debris deposited on the fan by a flow in 1989.

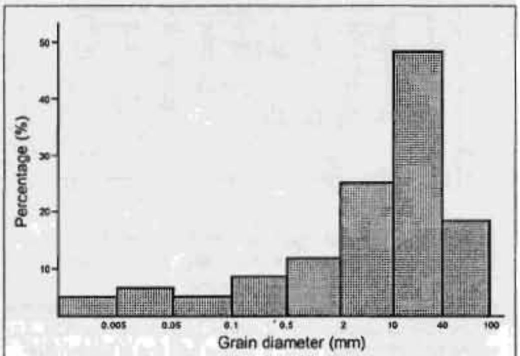

Figure 18.15: **Grain diameter of solid material deposited by a low viscosity debris flow in 1989**

Damage

The railway, highway and irrigation canal pass parallel to each other through the lower reach of the Laogan Ravine (Figure 18.14). As the railway line is at the lower level, it was most exposed to damage from the debris flows.

The railway was constructed across the ravine in the spring of 1959. A debris flow in July of the same year silted up the 60m long bridge and washed away a large section of the railway bed near the bridge. A new ravine canal developed. In 1960, a larger four span bridge was constructed across the ravine. This bridge also gradually silted up between 1961 and 1970. The average rate of deposition was 70 cm per year. In 1971, an open tunnel more than 100m long and a 150m long protection dyke were built above the silted bridge.

Figure 18.16: **View of the covered tunnel and fan of the Laogan Ravine. The left outlet of the tunnel was silted up by about 3m as a result of the July 1987 flood**

The large debris flow in 1985 buried the open tunnel. After this a covered tunnel was built over which debris flows could pass down into the Xiaojiang river. In July 1987, this tunnel was submerged by a flood and the left outlet of the tunnel was silted up to a height of about 3m (Figure 18.16).

The railway department spent about US$ 3.25 million between 1959 and 1989 to try and prevent damage to the railway,. During the same period, the ravine course bed silted up by about 30m rising from 1,305m to 1,335m altitude with an average rate of deposition of 1m per year (Figure 18.17).

The highway runs 80m upstream of the railway. In the beginning a small bridge was constructed across the ravine course, which was however soon destroyed. A pavement (causeway) was constructed over the destroyed bridge to allow debris to flow down it. A flood in May 1990 also damaged the causeway (Figure 18.18). The annual cost of repairing and maintaining this sec-

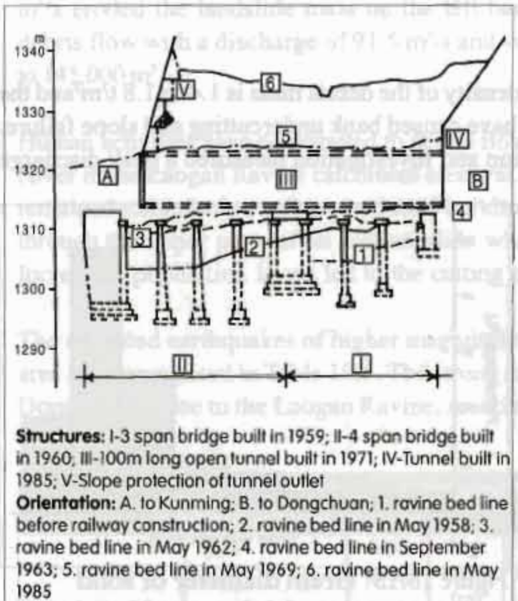

Figure 18.17: **Cross section of the Laogan Ravine at the level of the railway showing engineering structures and extent of silting**

Figure 18.18: **The causeway of the highway constructed over the destroyed bridge over the Laogan Ravine. The bridge was damaged by a debris flow in May 1990**

tion of the highway has been US$ 25,000. Adding the cost of the new bridge, the total comes to more than US$ 0.67 million.

The Tuanjia irrigation canal is situated 50m upstream of the highway and was constructed in 1958. Very large debris flows in 1985 and 1987 destroyed the canal tunnel, causing losses amounting to more than US$ 50,000. As well as damaging the infrastructure, the disastrous debris flow of 26 June 1985 killed 12 people and injured 3 in a moving bus which was washed away by the flow.

As none of the structures constructed by the Department of Railways and Highways to prevent debris flows in the ravine has been successful, control of this debris flow, and the need to develop a different approach, became an important issue.

Integrated control measures

In 1988 the Dongchuan Institute of Debris Flow Protection was approached by Dongchuan City authorities to conduct detailed investigations of the debris flow ravine and design control measures with assistance from the Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences (CAS). The detailed investigations indicated that the formation of the debris flow in the ravine was mainly associated with the large landslide on the south slope of the lower reaches of the ravine valley (Figures 18.19 and 18.20). The railway and highway could not be saved without stabilising this large landslide and channelling the ravine's course. An integrated control plan was prepared based on detailed field investigation and analysis, and implemented by the two institutions in collaboration with local communities between 1991 and 1994. The debris flow control measures were designed:

- to improve the natural environment using bio-engineering with an emphasis on planting bushes and trees in the middle and upper reaches of the watershed;
- to combine civil engineering and bio-engineering to obtain the best benefit from the control measures;
- to stabilise the large landslide of the south bank and channel the main stream course in the lower reaches.

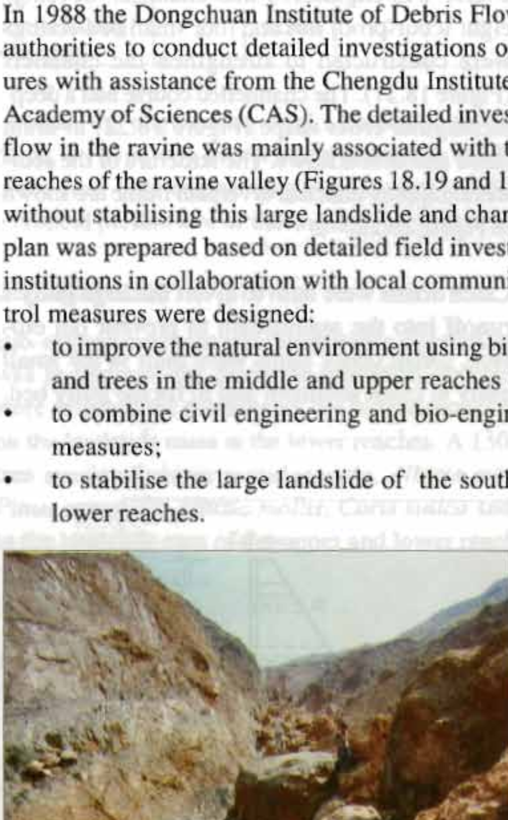

Figure 18.19: View of debris flow forming area in the upper lower reaches of the Laogan Ravine (looking upstream in 1988). In the past, abundant loose solid materials of landslide mass from here contributed to debris flows during heavy rain storms

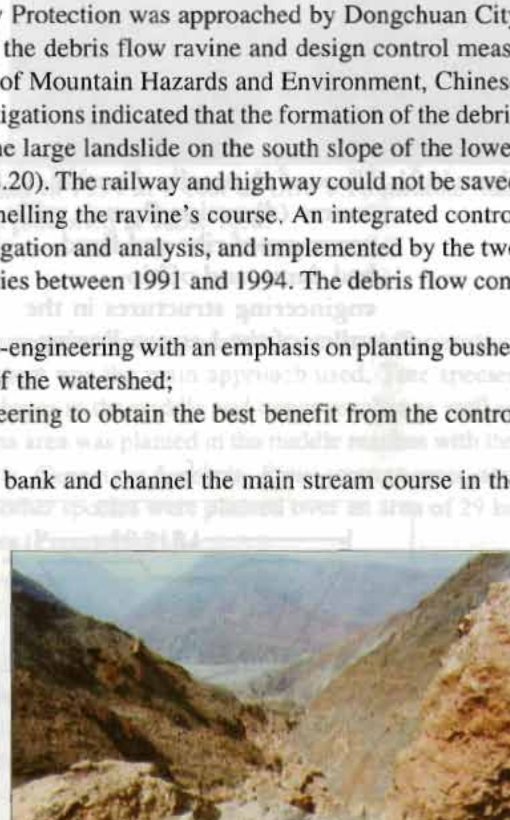

Figure 18.20: View of debris flow forming area of the Laogan Ravine (looking downstream in 1988). Bank erosion and collapses provided abundant loose materials to form debris flows.

Landslide stabilisation was one of the major tasks since the large landslide was the main source of loose solid materials. Two 17.5 m high sediment-trapping dams were constructed at the toe of the landslide to control down cutting and toe erosion (Figure 18.14). A 155m long protective dyke and eight small check dams were also constructed in the landslide area to control side and gully erosion.

Figure 18.21: **View of channelised ravine course (diversion flume), with scour-proof ribs and fixed-bed dams, and of bio-engineering structures in the valley of the Laogan Ravine**

Both sides of the mainstream between the altitudes of 1,397m and 1,454m are composed of loose sediments so that it was important to channelling the course of the mainstream to prevent down-cutting and side erosion: 1080m of stream course was engineered into channels. Seventy-eight scour-proof ribs and four small bed-fixings were constructed to strengthen the channels (Figure 18.21). The channelled course had a deep-rectangular cross shape (Figure 18.22) to drain flood and debris flows. The structure of the sediment trapping dam and diversion flume are shown in Figure 18.22.

Catch drains were built to divert the large gully's runoff into the mainstream to prevent fan erosion. Small check dams were built in the small gully to catch sediment and to fix the gully bed.

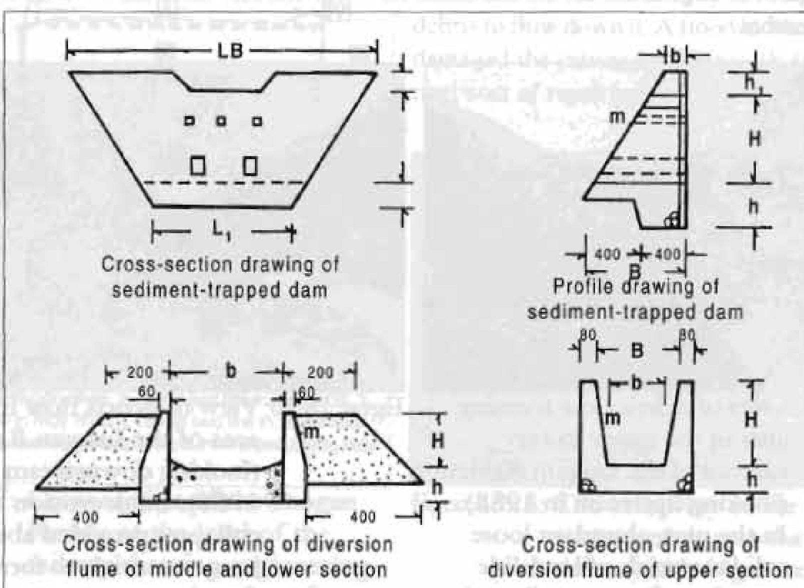

Figure 18.22: **Plan of the sediment-trapping dam and diversion flume (for actual values see Table 18.6)**

Table 18.6: **Technical parameters of civil engineering works** (dimension labels shown in Figure 18.22)									
Structure	H (m)	m	B (m)	B (m)	L1 (m)	L2 (m)	h1	Spillway section (m)	Note
Catch dam 1	9.0	1:0.4	1.0	5.0	28.0	36.5	2.0	9 x 2	Small holes for drain 0.6 x 0.8 m
Catch dam 2	8.5	1:0.7	2.0	8.8	15.0	33.0	3	9 x 2	Big holes for drain 1x2m
Steep flume	3.0	1:0.15	2.6	3.0	20		1	2.5 x 3	
One-side flume	3.0		1.0	2.0	610		1.5	8 x 3	
Two-side flume	3.5	1:04	0.6	1.8	476		2.5	8 x 3.5	
Catch drain	3.5	1:0.25	1.5	0.6	60		1.5		
Fix-bed dams (4)	2.5-3.0	1:02	0.8-1.0	1.5-2.5	8-10	8-10	5-5.5	10 x 2.5	height and width varies
Check dams (8)	3-7	1:05	1-1.5	3-4	6.0	10.0	1.5-2.0	6 x 2	height and width varies
Anti-scouring ribs (78)		1:0.25	1.0	1.6	11.6	11.6	2.5	8 x 3.5	height and width varies

In total, the engineering works consisted of two main dams, four bed-fixing dams, eight check dams, a 155m long protection dyke, and a 1080m long diversion flume with seventy-eight scour-proof ribs. The engineering works were completed in 1994 at a cost of US$ 0.16 million. The technical parameters of the engineering works are presented in Table 18.6.

Bio-engineering

Bio-engineering was used to increase vegetation cover and prevent surface erosion. Afforestation was to improve the degraded mountain environment was the main approach used. Tree species were selected for planting on the bare mountain slopes in the middle and upper reaches as well as on the landslide mass in the lower reaches. A 130 ha area was planted in the middle reaches with the tree species *Robinia pseudoacacia*, *Albizia mollis*, *Cupressus funebris*, *Pinus yunnanensis*, and *Pinus armandii*. *Albizia mollis*, *Coris sinica* and other species were planted over an area of 29 ha in the landslide area of the upper and lower reaches (Figure 18.21).

Impact assessment

The sediment-trapping dams arrested about 42,000 m^3 sediment and stabilised the main landslide by raising the level of the ravine above the toe of the landslide. The 1,080m long artificial diversion flume confined the flood and prevented side erosion of the ravine, which greatly reduced the sediment released. Before the measures were taken, about 150,000 m^3 of loose solid materials were transported in the form of debris flow down to the Xiaojiang River. After completion of the engineering works in 1994, only sediment laden flow and light erosion has been observed in the lower reaches of the ravine.

The tree plantations in the middle and upper reaches covered 130 ha. Thanks to the participation of local people, the rate of survival of the planted trees has been 90.4%. The estimated profit from these trees over 20 years will be US$ 590/ha/yr, i.e., US$ 77,000 – all income for the local people. Twenty-nine hectares of the landslide area was planted with *Albizia mollis* and *Coris sinica*. The estimated profit from these trees over five years is US$ 92/ha per year, a further $2,600. Apart from the economic benefits, this vegetation plays an important role in soil erosion control and shallow landslide stabilisation in the middle and upper reaches of the ravine.

Figure 18.23: **New bridge built in 1994 across the Laogan Ravine, the diversion flume can be seen under the bridge**

The debris flow in the Laogan Ravine caused US$ 4,875,000 in economic looses between 1958 and 1988. The cost of the control project was only US$ 169,000. There have been no debris flows in the ravine since the completion of the control measures. With the construction of a new bridge across the Laogan Ravine in 1994 (Figure 18.23), the reliability of transport flow has greatly improved.

Conclusions

Debris flows are a common hazard in mountain areas, and sometimes cause catastrophic disasters when they destroy houses, roads, and property. The debris flows in the two drainage areas studied are believed to have been largely caused by deforestation. Following deforestation, other factors such as the weak geologic materials, the high intensity of monsoon rainstorms, and high seismicity undoubtedly also contributed to triggering the landslide-debris flow processes.

In general, debris flow watersheds can be divided into a formation zone, a transportation zone, and a deposition zone. In most cases, landslides in the upper and middle reaches are the formation zone of debris flows.

Debris flow control projects can be successful only when there is a full understanding of the landslide and debris flow processes in the watershed concerned. The key part of the debris control programmes in the two case studies was to build a series of check dams to

- reduce sediment discharge by arresting debris from gully erosion and landslide areas;
- stabilise landslides and potential slope failures by back siltation behind the check dams; and
- prevent down cutting of the ravine by arrested sediment.

Once the dams are filled, the local gradient is also lower and the valleys slightly wider. However, once a group of check dams along a tributary have been filled in, additional retention of material within a ravine is limited unless the heights of the check dams are raised or material is removed. The effectiveness of check dams can be only partial and temporary if a large supply of debris is still entering a channel. Therefore it is necessary to have a comprehensive programme using bio-engineering and reforestation to control the supply of debris, as well as the construction of check dams and other engineering works. Trees and other plants are usually well-established and begin to act effectively to control erosion within five to ten years of planting. The cost of debris flow control is high, but the benefits often justify the investments.

Where possible, the alignment of linear infrastructures such as roads and irrigation canals should avoid the deposition zone of debris flows. Measures to mitigate damage from debris flows to existing highways, railways, and other infrastructures that are located in the deposition zones of debris flows should emphasise controlling slope instabilities in the middle and upper reaches and improving the environmental conditions of the catchment areas. Line agencies such as the Department of Roads need to co-operate with other departments and in particular with the local community and the government for the long-term mitigation of debris flow hazards.