PERGAMON

Tunnelling and Underground Space Technology 16 (2001) 133–150

Tunnelling and Underground Space Technology

www.elsevier.com/locate/tust

Tunnelling in Taiwan

Assessment of damage in mountain tunnels due to the Taiwan Chi-Chi Earthquake

W.L. Wang[a], T.T. Wang[b,*], J.J. Su[a], C.H. Lin[a], C.R. Seng[a], T.H. Huang[b]

[a] *United Geotech Inc., Taipei, Taiwan, ROC*
[b] *Department of Civil Engineering, National Taiwan University, 1 Section 4 Roosevelt Road, Taipei, Taiwan, ROC*

Received 15 March 2001; received in revised form 10 August 2001; accepted 14 August 2001

Abstract

Tunnels, being underground structures, have long been assumed to have the ability to sustain earthquakes with little damage. However, investigations of mountain tunnels after the Chi-Chi Earthquake in central Taiwan revealed that many tunnels suffered significant damage to various extents. This work describes the findings of a systematic assessment of damage in the mountain tunnels in Taiwan after the earthquake. It was found that among the 57 tunnels investigated 49 of them were damaged. The damage patterns are summarized based on the characteristics and the distribution of the lining cracks. This systematic investigation, involving geological conditions, design documents, construction and maintenance records of these tunnels, has been conducted to assess the potential factors that may have influence on the various damage patterns and the earthquake loading for tunnels. The results show that the degree of damage is associated with the geological condition and structural arrangement of the tunnel. A tunnel passing through a displaced fault zone will definitely suffer damage. The extent of geological weak zones, distance from the epicenter, and the existence of a slope face are also significant influencing factors. The seismic capacity of the tunnel is influenced by its structural arrangement, type of lining, invert setup, lining reinforcement, and other parameters. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Tunnel damage; Earthquake; Lining cracks

1. Introduction

Mountain tunnels, being situated deep within rock layers, have generally been assumed to be sustainable against damage from earthquakes. Previous studies have found earthquake damage in tunnels to be localized at sections with two important characteristics: those running through displaced faults, which were damaged by shear forces that developed during the earthquake, and those near surface slopes (especially at portal sections), which were damaged owing to slope failures (Dowding and Rozen, 1978; Yoshikawa, 1981; Sharma and Judd, 1991; Asakura and Sato, 1996, 1998). Most of the design codes relating to earthquake mitigation for mountain tunnels are currently designed for use at portals and sections near slope surfaces, and seldom for other sections, including deeper mined parts and areas near intersections. Nevertheless, the Chi-Chi Earthquake inflicted significant damage on many tunnels in central Taiwan, such as cracking, spalling of concrete lining and deformation of steel reinforcement. This damage provides sufficient evidence to suggest that the effects of earthquakes on tunnels should be further studied.

To study the damage influencing factors, the results

* Corresponding author. Tel.: +886-2-2746-6777; fax: +886-2-2364-5734.
E-mail address: wangseeu@ms11.hinet.net (T.T. Wang).

0886-7798/01/$ - see front matter © 2001 Elsevier Science Ltd. All rights reserved.
PII: S0886-7798(01)00047-5

of investigations of 57 mountain tunnels affected by the Chi-Chi Earthquake were presented in this paper. For each tunnel, the damage patterns are examined on the basis of crack mapping results, and the degree of damage was assessed based on its functionality after the earthquake. Tunnel damage, geological and geotechnical conditions and tunnel structural characteristics are systematically investigated to evaluate the factors influencing tunnel damage in an earthquake. This paper also discusses the influence of seismic effects on tunnel engineering.

2. Brief description of the Chi-Chi Earthquake

On 21 September 1999, at 01.47 h local time, a strong earthquake with a magnitude of 7.3 on the Richter scale occurred near the town of Chi-Chi in central Taiwan (N23.78°, E120.84°), at a depth of approximately 7.5 km. The island suffered catastrophic damage during the earthquake, with 2375 lives being lost, over 10 000 people being injured and more than 30 000 buildings collapsed.

The Chi-Chi earthquake resulted from the reactivation of the Chelungpu Fault. The fault was long ago identified as a thrust fault, running in a N–S direction for a total length of 60 km, while dipping eastward at an angle of 30° or less. However, visually identified surface ruptures following the earthquake indicated that the fault is more extensive. It has a total length of 85 km, including newly formed branches at the northern tip of the fault, as shown in Fig. 1. This growth of the fault represents the largest known onshore thrust-faulting event of the 20th century.

Geologically, the fault is easily identifiable. The formation on the east of the fault, i.e. the hanging wall, consists of late Pliocene Chinshui Shale and early Pleistocene shaley Cholan Formation, while the west of the fault, the footwall, consists of gravelly late Pleistocene Toukershan Formation.

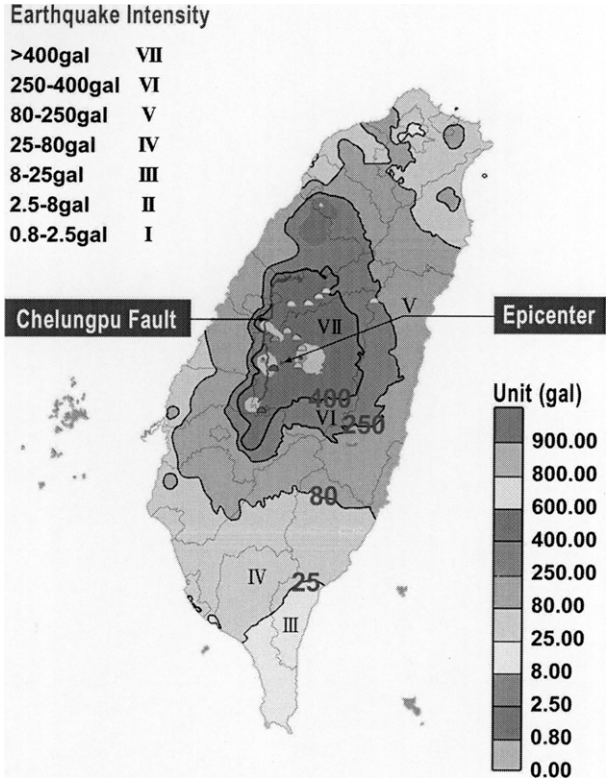

Fig. 1. Intensity of Chi-Chi Earthquake felt at different locations in Taiwan (after National Central University, 2001).

The Chi-Chi earthquake caused significant ground

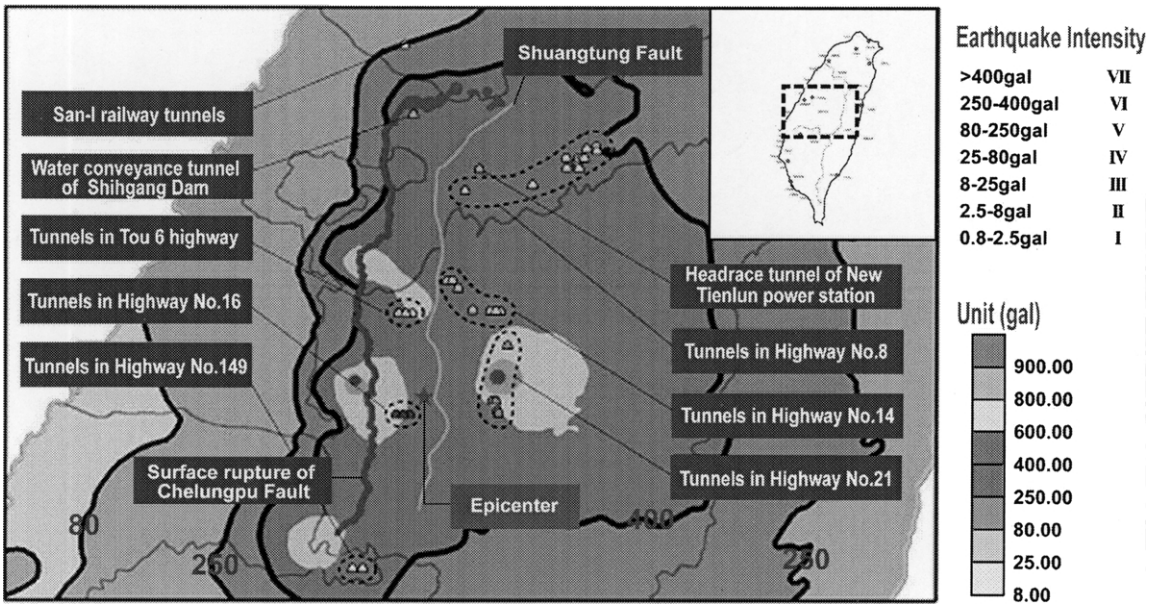

Fig. 2. The location of tunnels investigated and the earthquake intensity on ground surface.

Table 1
Tunnels investigated and their damage types

No.	Tunnel and location	Basic information					
		Tunneling Method[a]	Length (m)	Width (m)	Lining	Distance to the epicenter (km)	Distance to Che-Lung-Pu fault (km)
1	Shih-Gang Dam, Water conveyance tunnel	NA TM	–	–	Y	–	0.0
2	Highway 8, 13k + 381	T	20	6.5	N	35.1	12.0
3	Highway 8, 27k + 710 Li-Lang Tunnel	T	30	6.8	N	38.6	18.6
4	Highway 8, 34k + 668	T	50	3.2	Y	44.0	20.1
5	Highway 8, 34k + 775	T	41	3.4	Y	44.0	20.1
6	Highway 8, 35k + 908 old Ku-Kuan Tunnel	T	90	5.1	Y	44.8	19.8
7	Highway 8, 36k + 908 Ku-Kuan Tunnel	T	90	7.5	Y	44.8	19.8
8	Highway 8, 38k + 500 No.1 old Maa-Ling Tunnel	T	150	4.0	Y	45.9	21.5
9	Highway 8, 38k + 500 No.1 Maa-Ling Tunnel	T	365	5.1	Y	45.8	21.5
10	Highway 8, 39k + 075 No.2 Maa-Ling Tunnel	T	60	7.5	Y	46.1	21.6
11	Highway 8, 40k + 830 No.3 Maa-Ling Tunnel	T	245	7.5	Y	46.3	21.6
12	Highway 8, 41k + 311 No.4 Maa-Ling Tunnel	T	100	7.5	Y	47.8	22.1
13	Highway 8, 41k + 311 No.4 old Maa-Ling	T	100	4.0	Y	47.8	22.1
14	Highway 8, 42k + 573	T	10	6.5	N	48.3	23.0
15	Highway 8, 43k + 040	T	15	6.5	N	48.3	23.0
16	Highway 8, 45k + 266	T	32	6.5	Y	48.5	22.8
17	Highway 14, 37k + 405 Shuang-Fu Tunnel	T	150	7.5	Y	19.7	12.0
18	Highway 14, 37k + 981(L) Gang-Lin Tunnel	T	182	7.5	Y	19.8	12.2
19	Highway 14, 38k + 000(R) Gang-Lin Tunnel	T	249	7.5	Y	19.8	12.2

Table 1 (*Continued*)

No.	Tunnel and location	Basic information					
		Tunneling Method[a]	Length (m)	Width (m)	Lining	Distance to the epicenter (km)	Distance to Che-Lung-Pu fault (km)
20	Highway 14, 39k + 921(L) Yu-Ler Tunnel	T	158	7.5	Y	19.0	13.8
21	Highway 14, 39k + 921(R) Yu-Ler Tunnel	T	158	7.5	Y	19.0	13.8
22	Highway 14, 45k +182 Pei-Shan Tunnel	T	120	7.5	Y	15.9	17.5
23	Highway 14, 48k + 616(L) No.1 Kuan-Yin Tunnel	T	129	7.5	Y	17.1	20.4
24	Highway 14, 48k + 616(R) No.1 Kuan-Yin Tunnel	T	129	7.5	Y	17.1	20.4
25	Highway 14, 48k + 787(L) No. 2 Kuan-Yin Tunnel	T	123	7.5	Y	17.5	20.8
26	Highway 14, 48k + 787(R) No.2 Kuan-Yin Tunnel	T	123	7.5	Y	17.5	20.8
27	Highway 14, 49k + 253(L) No. 3 Kuan-Yin Tunnel	T	252	7.5	Y	17.6	21.2
28	Highway 14, 49k + 253(R) No. 3 Kuan-Yin Tunnel	T	252	7.5	Y	17.6	21.2
29	Highway 16, Chi-Chi Tunnel	T	238	4.8	Y	6.1	5.5
30	Highway 16, New Chi-Chi Tunnel (L)	NA TM	580	7.5	Y	6.4	5.3
31	Highway 16, New Chi-Chi Tunnel (R)	NA TM	515	7.5	Y	6.4	5.3
32	Highway 21, 54k + 326(L) Da-Yuan Tunnel	NA TM	462	7.5	Y	14.2	21.8

Table 1 (*Continued*)

No.	Tunnel and location	Basic information					
		Tunneling Method[a]	Length (m)	Width (m)	Lining	Distance to the epicenter (km)	Distance to Che-Lung-Pu fault (km)
33	Highway 21, 54k + 326(R) Da-Yuan Tunnel	NA TM	444	7.5	Y	14.2	21.8
34	Highway 21, 66k + 940(L) Shue-Sir Tunnel	NA TM	185	7.5	Y	8.5	19.9
35	Highway 21, 66k + 940(R) Shue-Sir Tunnel	NA TM	185	7.5	Y	8.5	19.9
36	Highway 21A, 17k + 303 No. 1 Huan-Hu Tunnel	T	128	7.5	Y	9.3	20.2
37	Highway 21A, 17k + 253 No. 2 Huan-Hu Tunnel	T	61	7.5	Y	9.3	20.2
38	Highway 149, Tsao-Ling Tunnel	NA TM	505	7.0	Y	31.1	7.0
39	Highway 149, Ching-Shue Tunnel	T	52	7.5	N	32.0	3.7
40	Tou-6 highway, No. 1 Tu-Cheng Tunnel	T	100	6.5	Y	15.5	7.2
41	Tou-6 highway, No. 2 Tu-Cheng Tunnel	T	290	6.4	Y	15.3	7.6
42	Tou-6 highway, Shuang-Lung Tunnel (E)	T	140	5.3	Y	15.2	7.8
43	Tou-6 highway, Shuang-Lung Tunnel (W)	T	90	5.3	Y	15.2	7.8
44	Tou-6 highway, No. 1 Shuang-Tung Tunnel	T	80	4.5	Y	15.2	7.8
45	Tou-6 highway, No. 2 Shuang-Tung Tunnel	T	120	4.5	Y	15.2	7.8
46	Chi-Chi line railway, No. 1 tunnel	T	350	5.0	Y	6.1	5.5
47	Chi-Chi line railway, No. 2 tunnel	T	1400	5.0	Y	< 1	11
48	Chi-Chi line railway, No. 3 tunnel	T	250	5.0	Y	4.5	15.9
49	Chi-Chi line railway, No. 5 tunnel	T	150	5.0	Y	5.5	16.4

Table 1 (*Continued*)

No.	Tunnel and location	Basic information					
		Tunneling Method[a]	Length (m)	Width (m)	Lining	Distance to the epicenter (km)	Distance to Che-Lung-Pu fault (km)
50	Da-Kuan power station, headrace tunnel	T	–	–	Y	8.5	19.9
51	New Tien-Lun power station, headrace tunnel	NA TM	10 600	5.0	Y	40	18.6
52	Mountain line railway, No. 1 San-I Tunnel	NA TM	7540	9.1	Y	55	11.1
53	Mountain line railway, No. 2 San-I Tunnel	NA TM	260	9.1	Y	50	10.1
54	Mountain line railway, No. 3 San-I Tunnel	NA TM	520	9.1	Y	49	10.1
55	Mountain line railway, No. 4 San-I Tunnel	NA TM	455	9.1	Y	49	10.1
56	Old mountain line railway, No. 1 San-I Tunnel	T	230	5.0	Y	59	14.5
57	Old mountain line railway, No. 2 San-I Tunnel	T	730	5.0	Y	58	13.1

No	Tunnel and location	Damage description										Damage classification[b]		
		Portal failure	Sheared off lining	Slope failure induced tunnel collapse	Lining cracks	Concrete lining spalling	Water inrush	Exposed reinforcement	Lining displaced	Pavement cracks	Rockfalls in unlining section	Overall	Mined section	Portals
1	Shih-Gang Dam, Water conveyance tunnel		√									C		
2	Highway 8, 13k + 381										√	A	A	A
3	Highway 8, 27k + 710 Li-Lang Tunnel											A	A	A
4	Highway 8, 34k + 668	√			√							B	A	B
5	Highway 8, 34k + 775	√			√							B	A	B
6	Highway 8, 35k + 908 old Ku-Kuan Tunnel	√			√		√					B	A	B
7	Highway 8, 36k + 908 Ku-Kuan Tunnel	√			√							B	A	B
8	Highway 8, 38k + 500 No.1 old Maa-Ling Tunnel	√			√	√			√			C	B	C

Table 1 (*Continued*)

No	Tunnel and location	Damage description										Damage classification[b]		
		Portal failure	Sheared off lining	Slope failure induced tunnel collapse	Lining cracks	Concrete lining spalling	Water inrush	Exposed reinforcement	Lining displaced	Pavement cracks	Rockfalls in unlining section	Overall	Mined section	Portals
9	Highway 8, 38k + 500 No.1 Maa-Ling Tunnel	√			√	√	√	√	√			C	C	C
10	Highway 8, 39k + 075 No.2 Maa-Ling Tunnel	√										C	A	C
11	Highway 8, 40k + 830 No.3 Maa-Ling Tunnel	√			√							C	A	C
12	Highway 8, 41k + 311 No.4 Maa-Ling Tunnel											A	A	A
13	Highway 8, 41k + 311 No.4 old Maa-Ling				√	√			√			C	C	A
14	Highway 8, 42k + 573	√									√	C	C	C
15	Highway 8, 43k + 040	√									√	B	A	B
16	Highway 8, 45k + 266	√			√							C	B	C
17	Highway 14, 37k + 405 Shuang-Fu Tunnel				√							A	A	A
18	Highway 14, 37k + 981(L) Gang-Lin Tunnel	√		√	√		√					C	A	C
19	Highway 14, 38k + 000(R) Gang-Lin Tunnel				√		√			√		A	A	A
20	Highway 14, 39k + 921(L) Yu-Ler Tunnel				√	√						A	A	A
21	Highway 14, 39k + 921(R) Yu-Ler Tunnel			√	√							A	A	A
22	Highway 14, 45k +182 Pei-Shan Tunnel				√							A	A	A
23	Highway 14, 48k + 616(L) No.1 Kuan-Yin Tunnel				√							A	A	A
24	Highway 14, 48k + 616(R) No.1 Kuan-Yin Tunnel				√							A	A	A

Table 1 (*Continued*)

No	Tunnel and location	Damage description										Damage classification[b]		
		Portal failure	Sheared off lining	Slope failure induced tunnel collapse	Lining cracks	Concrete lining spalling	Water inrush	Exposed reinforcement	Lining displaced	Pavement cracks	Rockfalls in unlining section	Overall	Mined section	Portals
25	Highway 14, 48k + 787(L) No. 2 Kuan-Yin Tunnel				√		√					A	A	A
26	Highway 14, 48k + 787(R) No.2 Kuan-Yin Tunnel				√		√					A	A	A
27	Highway 14, 49k + 253(L) No. 3 Kuan-Yin Tunnel	√			√		√					B	A	B
28	Highway 14, 49k + 253(R) No. 3 Kuan-Yin Tunnel				√		√					A	A	A
29	Highway 16, Chi-Chi Tunnel				√		√					A	A	A
30	Highway 16, New Chi-Chi Tunnel (L)				√							A	A	A
31	Highway 16, New Chi-Chi Tunnel (R)				√	√		√				C	C	A
32	Highway 21, 54k + 326(L) Da-Yuan Tunnel				√							A	A	A
33	Highway 21, 54k + 326(R) Da-Yuan Tunnel				√							A	A	A
34	Highway 21, 66k + 940(L) Shue-Sir Tunnel				√							A	A	A
35	Highway 21, 66k + 940(R) Shue-Sir Tunnel											A	A	A
36	Highway 21A, 17k + 303 No. 1 Huan-Hu Tunnel											A	A	A
37	Highway 21A, 17k + 253 No. 2 Huan-Hu Tunnel											A	A	A
38	Highway 149, Tsao-Ling Tunnel	√			√	√		√				C	B	C
39	Highway 149, Ching-Shue Tunnel	√		√	√							C	C	C
40	Tou-6 highway, No. 1 Tu-Cheng Tunnel				√	√						A	A	A

Table 1 (*Continued*)

No	Tunnel and location	Damage description										Damage classification[b]		
		Portal failure	Sheared off lining	Slope failure induced tunnel collapse	Lining cracks	Concrete lining spalling	Water inrush	Exposed reinforcement	Lining displaced	Pavement cracks	Rockfalls in unlining section	Overall	Mined section	Portals
41	Tou-6 highway, No. 2 Tu-Cheng Tunnel				√	√						B	B	A
42	Tou-6 highway, Shuang-Lung Tunnel (E)				√					√		B	B	A
43	Tou-6 highway, Shuang-Lung Tunnel (W)				√							A	A	A
44	Tou-6 highway, No. 1 Shuang-Tung Tunnel	√			√	√						B	B	B
45	Tou-6 highway, No. 2 Shuang-Tung Tunnel				√	√						A	A	A
46	Chi-Chi line railway, No. 1 tunnel				√							A	A	A
47	Chi-Chi line railway, No. 2 tunnel				√							A	A	A
48	Chi-Chi line railway, No. 3 tunnel				√							B	B	B
49	Chi-Chi line railway, No. 5 tunnel				√							B	B	B
50	Da-Kuan power station, headrace tunnel				√			√				C	C	A
51	New Tien-Lun power station, headrace tunnel				√			√	√			C	C	A
52	Mountain line railway, No. 1 San-I Tunnel				√	√			√	√		C	C	A
53	Mountain line railway, No. 2 San-I Tunnel											A	A	A
54	Mountain line railway, No. 3 San-I Tunnel											A	A	A
55	Mountain line railway, No. 4 San-I Tunnel											A	A	A
56	Old mountain line railway, No. 1 San-I Tunnel				√	√						A	A	A
57	Old mountain line railway, No. 2 San-I Tunnel				√	√						A	A	A

[a] Tunnelling method: T means traditional tunneling method, NATM means New Austria Tunneling Method.

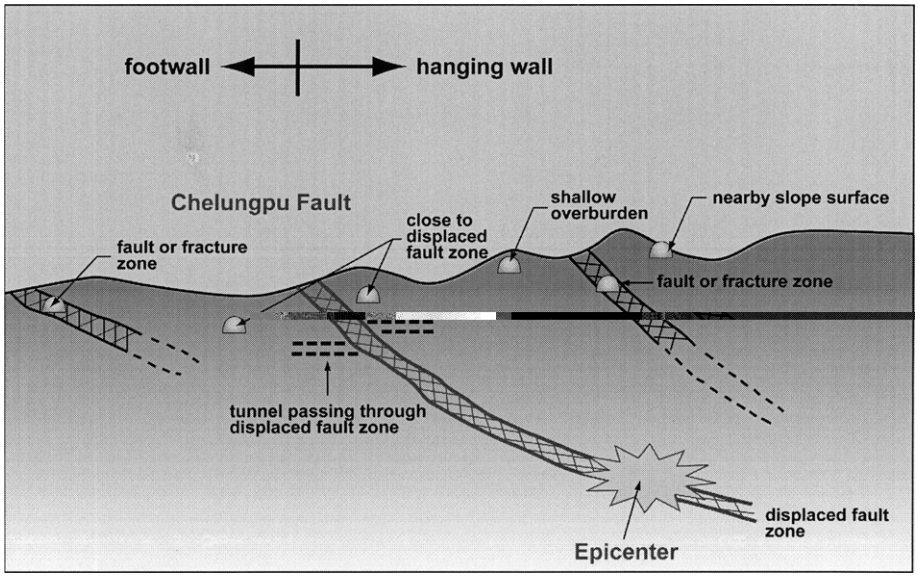

Fig. 3. Tunnel locations relative to Chelungpu thrust fault.

deformation. GPS survey results indicated that an area east of the fault with a width of approximately 15 km was displaced north-westwards, with a maximum horizontal displacement of 9.06 m (10 m horizontal displacement was measured on the ground), and vertically uplifted by approximately 9.8 m at the Shihkang Dam, near the north tip of the fault line. Fig. 1 shows the surface rupture and peak ground acceleration (PGA) contour caused by the earthquake.

3. Damage to mountain tunnels

Following the earthquake, a systematic investigation was conducted on 57 tunnels located in central Taiwan. Firstly, quick visual inspections were performed within a couple of days of the earthquake to gather preliminary information on tunnel damage. Detailed surveys were then performed for tunnels that were significantly damaged, using lining crack mapping, photo recording, and measuring of the major crack characteristics (including width, depth and relative displacement direction). Non-destructive inspection methods, such as ground penetration radar (GPR), were also used in several severely damaged tunnels. Fig. 2 indicates the locations of the investigated tunnels and the intensity of the earthquake on the ground surface.

Various types of damage were observed, including lining cracks, portal failure, concrete lining spalling, groundwater inrush, exposed and buckled reinforcement, displaced lining, rockfalls in unlined sections, lining collapses caused by slope failure, pavement or

Fig. 4. The numbers of tunnels suffering various types of damage.