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Geological and geomorphological precursors of the Chiu-fen-erh-shan landslide triggered by the Chi-chi earthquake in central Taiwan

Wen-Neng Wang[a,*], Masahiro Chigira[b], Takahiko Furuya[c]

[a] *Industrial Technology Research Institute, L400 ERL/ITRI, Chung Hsing Road, Chungtung, Hsin-chu 310, Taiwan*
[b] *Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji 611-0011, Japan*
[c] *Graduate School of Science and Technology, Chiba University, Yayoi, Inage, Chiba 263-8522, Japan*

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Abstract

Special features were correlated to the geological causes of the Chiu-fen-erh-shan landslide, a gigantic rockslide on a dip slope, induced by the Chi-chi earthquake ($M_L = 7.3$) in central Taiwan in 1999. An aerial photo interpretation and the succeeding geological mapping of the failure were employed in this study. A linear depression, a steep step, and a low drainage density in the landslide area were detected from the aerial photos taken in 1998. The gravitational creep was believed to result in the features of the linear depression and the low drainage density. The steep step represented a buckling feature found in the field. The landslide area is composed of stratified sandstone and shale, with dip angles ranging 20–36°. The slip surface developed along a pre-existing bedding fault that resulted from flexural slip folding. Before the Chi-chi earthquake, the rock on the upslope side buckled and was retained by a thick-bedded sandstone downslope. The earthquake shock seriously damaged the sandstone support and led to the catastrophic landslide. This type of landslide is likely to occur on the moderately dipping slope of stratified rocks that were previously deformed by flexural slip folding.

Keywords: Earthquake; Landslide; Flexural slip; Buckling; Chi-chi earthquake

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1. Introduction

An earthquake took place in central Taiwan on September 21, 1999. The earthquake is called “Chi-chi earthquake” for its epicenter (23.85°N, 120.81°E) was near Chi-chi, a small town in central Taiwan. The magnitude was $M_L = 7.3$, measured by the Central Weather Bureau (CWB) in Taiwan, or $M_S = 7.7$ by the US Geological Survey. The focal depth was about 10 km. This shallow earthquake killed about 2400 persons, injured 8700 people, destroyed over 6000 buildings, and made 100,000 people homeless. About 26,000 earthquake-induced slope failures were identified from the analysis of aerial photos covering an area of 375,000 ha (Wang et al., 2000). The sum of total failure areas reached 16,000 ha. The failure rate,

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* Corresponding author. Fax: +886-3-582-0017.
E-mail address: WenNengWANG@itri.org.tw (W.-N. Wang).

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a percentage of the total failure area to the analyzed area, was about 5%. More than 90% of the slope failures were small, generally equal or less than 1 ha. Nevertheless, the Chi-chi earthquake also triggered some gigantic slope failures. The Chiu-fen-erh-shan landslide was one of the most notorious ones in this event (Kamai et al., 2000; Lee, 2000; Furuya, 2001; Fig. 1).

The Chiu-fen-erh-shan landslide is located about 10 km northeast of the epicenter (23.85°N, 120.81°E). The peak ground acceleration (PGA) recorded by a CWB seismic monitoring station about 6 km north of this landslide was 465.3 gal in east–west component, 370.5 gal in north–south component, and 274.7 gal in vertical component during the Chi-chi earthquake. The mass moved along the bedding plane with a strike/dip of N30°–50°E/SE20°–36°. The materials that slid were chiefly composed of thick-bedded muddy sandstone with subordinate shale, with an estimated volume of 50×10^6 m^3. The slid materials buried 39 persons and 228 Asiatic deer, and blocked a confluence of two streams, leading to the formation of two ponds. One pond was 4.4 ha in size and 29 m in depth, and the other was 6.4 ha in size and 37.5 m in depth. The failed area was 102 ha and the deposited area was 92.5 ha. Therefore, about 200 ha of farming land was devastated by this landslide disaster.

Large landslides, particularly rockslide-avalanche, can move very fast and far more than 10 km away (Mudge, 1965; Voight, 1978), such as the 1984 Mt. Ontake landslide in Japan (Endo et al., 1989; Voight and Sousa, 1994). The indicators or precursory phenomena of slope instability should be recognized beforehand so as to avoid or mitigate such a catastrophic landslide disaster. The geological characteristics of a site are the important and basic causes of landslides, particularly for a deep-seated gigantic landslide whose cause is complicated. But precursory phenomena of a large and catastrophic landslide are sometimes expressed in special landforms (Chigira and Kiho, 1994; Chigira, 2001), such as the outer ends of dipping strata showing a downward bending (Cassie, 1978), and intermittent eyebrow-shaped scarplets or linear depressions on the upslope (Chigira, 2001).

The main purpose of this study is to correlate the geological and the geomorphological features to the basic causes of the Chiu-fen-erh-shan landslide, and

Fig. 1. Overview of the Chiu-fen-erh-shan landslide, looking to the southeast.

then examine the potentiality of those features serving as precursory indicators. Interpreting the aerial photos taken in 1998 with a later field survey is adopted in the study.

2. Geology

Taiwan is situated on a convergent and compressive boundary between the Eurasian plate and the Philippine Sea plate (Fig. 2). The Philippine Sea plate moves 7 cm/year northwestward to the Eurasian plate (Ho, 1982). The topographic relief of the western central Taiwan increases in altitude from west to east, with plains and rolling hills in the west and high mountains in the east. The western central Taiwan is mostly composed of Tertiary sedimentary and sub-metamorphic rocks (Fig. 2). These rocks generally age and indurate eastward (Ho, 1986). North-trending longitudinal faults, from west to east, called the Chelungpu fault, the Shuangtung fault, the Shuili fault, and the Lishan fault traverse the

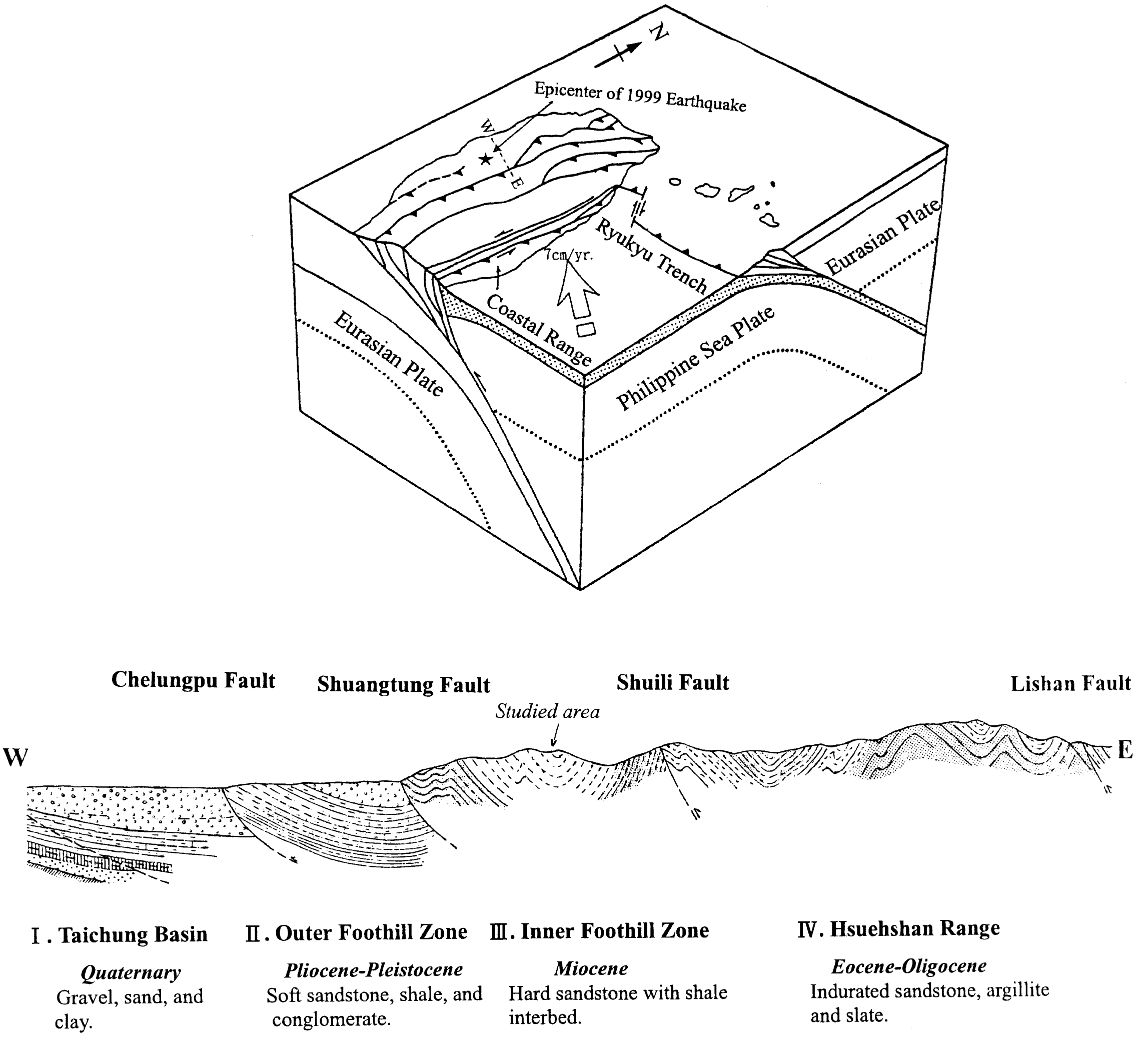

Fig. 2. Plate tectonic setting of Taiwan and schematic cross-section of central Taiwan along E–W line (not to scale).

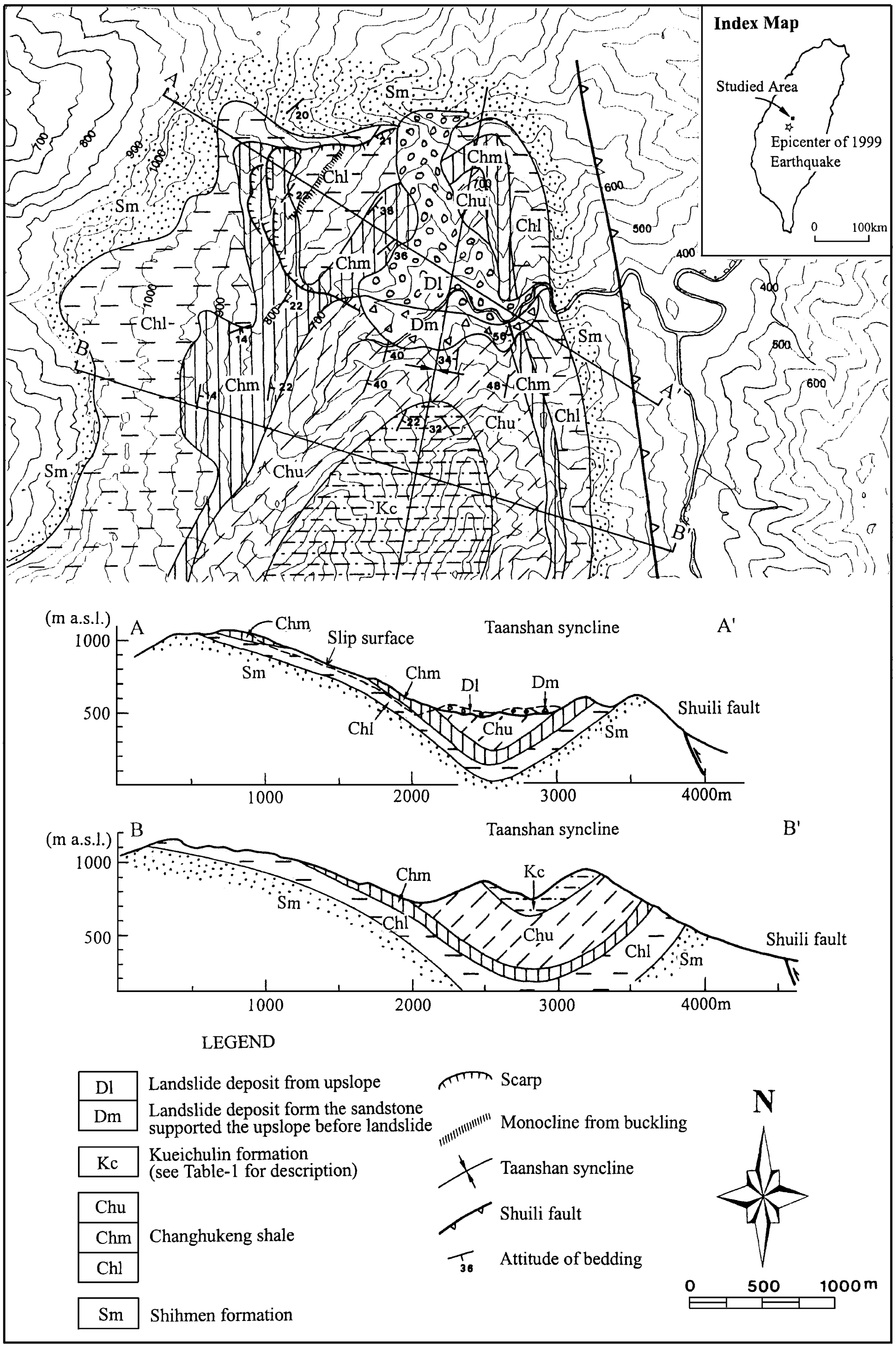

Fig. 3. Geologic map and cross-section of the landslide site.

Table 1
Brief description of the strata in the studied area

Strata	Character	Thickness (m)
Kueichulin Formation (Kc)	gray massive sandstone with subordinate shale.	500
Changhukeng Shale		
Upper member (Chu)	shale alternated with fine sandstone and siltstone.	200
Middle member (Chm)	thick-bedded to massive, fine sandstone.	100
Lower member (Chl)	massive shale with thin sandstone interbeds.	80–100
Shihmen Formation (Sm)	massive muddy sandstone with thin shale.	>100

western central Taiwan and divide it into four geological zones: the Taichung basin, the outer foothill zone, the inner foothill zone, and the Hsuehshan range (Fig. 2). The plate collision accumulates strain along active faults in western Taiwan. The Chelungpu fault, an active fault in western Taiwan, was reactivated during the Chi-chi earthquake in 1999.

The study area is located in the inner foothill zone, and is underlain mainly by Miocene sedimentary rocks. The strata exposed in this area are, in ascending order, the Shihmen Formation (Sm), the Changhukeng Shale, and the Kueichulin Formation (Kc) (Ho et al., 1956; Ho and Tan, 1960; Ho, 1986) (Fig. 3; Table 1). The strata are folded with an N–S trending synclinal axis in the eastern part (Fig. 3).

The Shihmen Formation (Sm) consists mainly of light gray muddy sandstone with thin-bedded dark gray shale. The sandstone is massive to thick-bedded,

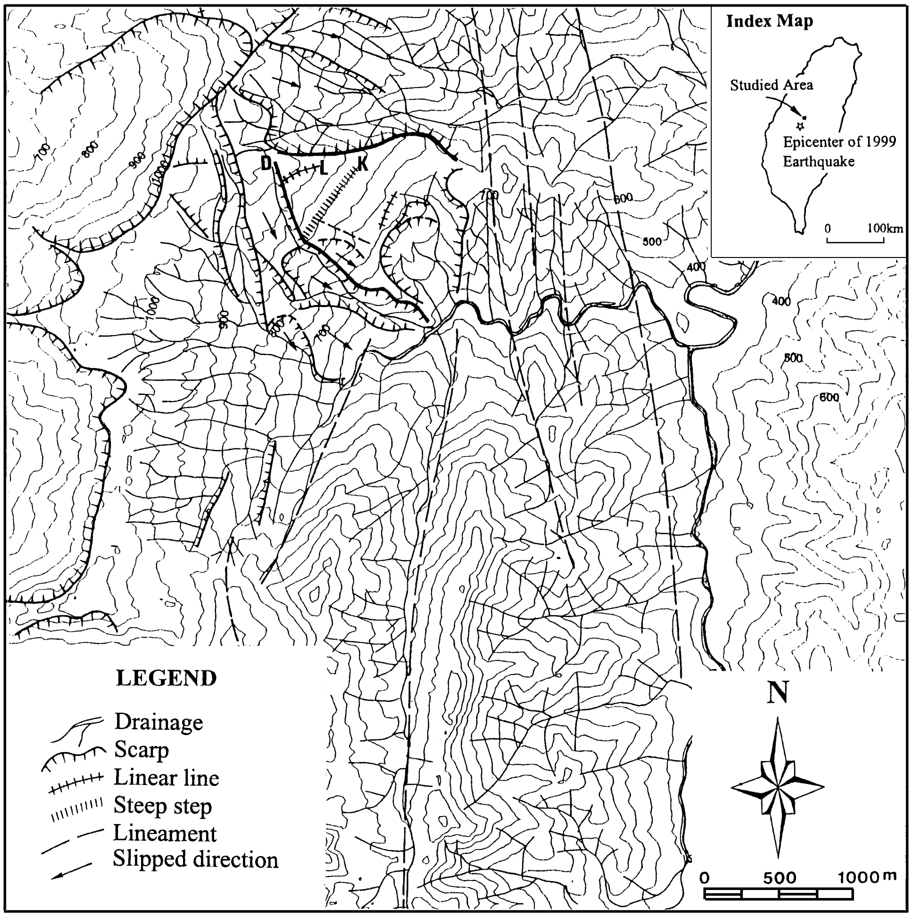

Fig. 4. Geomorphological map before the landslide, mainly based on aerial photo interpretation.

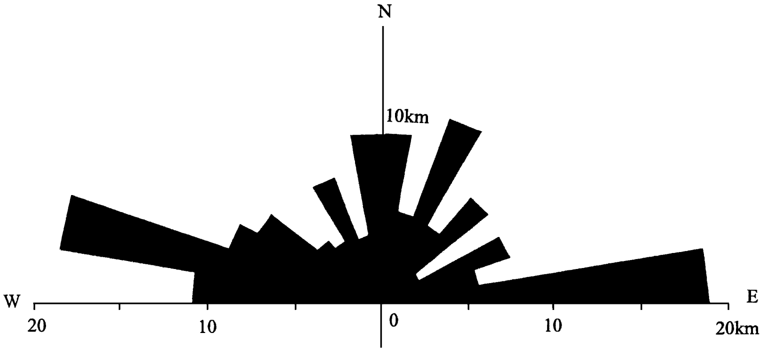

Fig. 5. Accumulated length of drainage ways according to the drainage direction.

fine-grained and compact, with shale or sandy shale interbeds. This formation is easily traced in the aerial photographs and in the field due to the steep cliffs formed by the sandstone. The Shihmen Formation in this area is over 100 m thick.

The Changhukeng Shale is composed of dark gray marine shale with subordinate sandstone. The shale is generally massive, but bedding with ripples is well distinct where it contains interbeds of siltstone or sandstone. This formation can be subdivided into lower, middle, and upper members. The lower member (Chl), 80–100 m thick, is composed of massive and compact shale with thin sandstone interbeds. The middle member (Chm) is thick-bedded to massive, gray, fine sandstone, about 100 m thick. The upper member (Chu), more than 200 m thick, consists of shale with thin, fine, and dense sandstone and siltstone, and these beds sometime alternate as 2–20 cm-thick beds.

The Kueichulin Formation (Kc) is distributed along the axis of the Taanshan syncline in the southern part of the studied area. It is represented by gray to yellowish brown massive sandstone with subordinate shale. The observable thickness is about 500 m.

The strata in this area are folded to form the Taanshan syncline. The synclinal axis trends nearly in the N–S direction and slightly plunges southward. The observed dips on the western limb of the syncline are 20–40°; those on the eastern limb range 30–60°. This syncline is a flexural-slip fold, which resulted in bedding faults with a few clayey shear zones, up to 5 cm thick, containing dip slip striations. The bedding faults can be observed at several locations in and around the landslide area.

3. Geomorphological features before 1999 landslide

Anomalous features such as a linear depression, a steep step, and low drainage density can be found within the Chu-fen-erh-shan landslide area by examining the aerial photos of 1998 (Fig. 4). The landslide is situated on a dip slope facing SE. The plane view of the dip slope forms an isosceles triangle with northern and southwestern sides bounded by scarps (as indicated by thick lines in Fig. 4). The short linear depression (as indicated by L in Fig. 4), which could be induced by creeping, connects these two sides on the upper part of the dip slope. The steep step (as indicated by K in Fig. 4), trending NE–SW, can be detected from the aerial photos taken in 1998.

Table 2
Drainage length and density in the area measured

	Drainage length (km)	Area (km^2)	Drainage density[a] (km^{-1})
Taanshan syncline			
Eastern limb	52.8	10.5	5.0
Western limb	42.4	8.1	5.2
Chiu-fen-erh-shan landslide	3.7	1.5	2.5

[a] Drainage density = Drainage length/Area.

The major stream in the studied area flows from south to north and then turns to east. The secondary streams basically develop along the dip slopes and nearly perpendicularly join the major stream to constitute a trellised drainage system in this area, an evidence of well-jointed bedrock. The EW- and NS-trending drainages are prevalent in this region, as indicated from an analysis of accumulated drainage

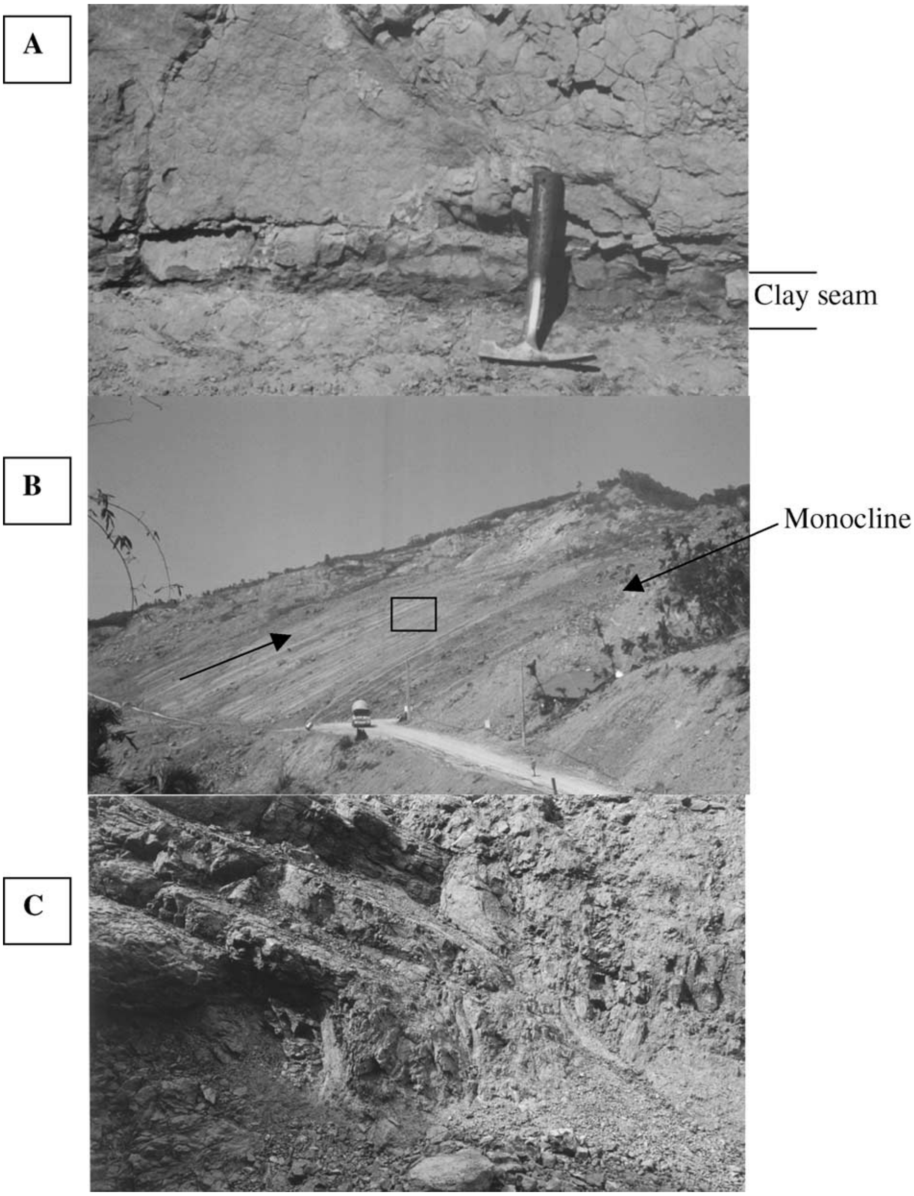

Fig. 6. Geologic features observed in the landslide source area. (A) A clay seam which is inferred to be made by flexural slip during the folding. (B) Upper part of the landslide scar, in which monocline appeared on the slip surface after the landslide. The slip surface becomes steeper downslope. (C) Close up of the box in (B).

length with respect to drainage direction (Fig. 5). The EW-trending drainage ways are notably perpendicular to the axis of the Taanshan syncline.

The average drainage density was about 5 km^{-1} in the studied area before the 1999 landslide (Table 2). The Chiu-fen-erh-shan landside only occupies a small part of the western limb of the Taanshan syncline. The drainage density of the landslide area was 2.5 km^{-1}, much lower than the average value (5.2 km^{-1}) for the western limb. This anomaly will be discussed further in Section 5.3.

4. Observations on the slip surface

The slip surface of the Chiu-fen-erh-shan landslide had been covered by debris just after the earthquake event, but was later exposed by the subsequent rain washing. The slip surface is smooth and parallel to the bedding plane, whose strike/dip are N30°E/SE22° on the upslope and N30°E/SE36° on the downslope. The crown and the foot of the landslide slope had been underlain by thick-bedded sandstone with a little shale (Chm) before the 1999 slide, as confirmed by a detailed mapping after the 1999 landslide. The 1999 landslide stripped off the sandstone of Chm and exposed the slip surface in the alternating beds of dark gray shale and sandstone of Chl (see the A–A′ cross-section in Fig. 3). Clay seams of 1–6 cm thick were found to be intercalated in the alternating beds, in which slickensides and dip slip striations were clear (Fig. 6A). The clay seams were apparently formed during flexural slip folding, as will be discussed later. An X-ray diffraction analysis revealed the clay seams to consist of quartz, feldspar, chlorite, illite, and a small amount of likely chlorite/smectite mixed layer clay minerals. The constituent minerals were the same as those of the parent rocks, indicating that the clay seams have rarely suffered chemical weathering.

A localized monocline, which trends N50°–60°E and extends for 500 m, was found on the upper part of the slope along the slip surface (Figs. 3 and 6B,C). The monocline is a step-like fold in which the upper limb and the lower limb are connected by a steep middle limb. The strata on the upper and the lower limbs dip 20° and 23°, respectively, and the middle dips 40–50°, forming a 5-m-high step. The hinge of the monocline is relatively smooth and not jagged, implying that the deformation of the slip surface was prior to the 1999 landslide. Because this monocline just underlay the steep step of the slope before the

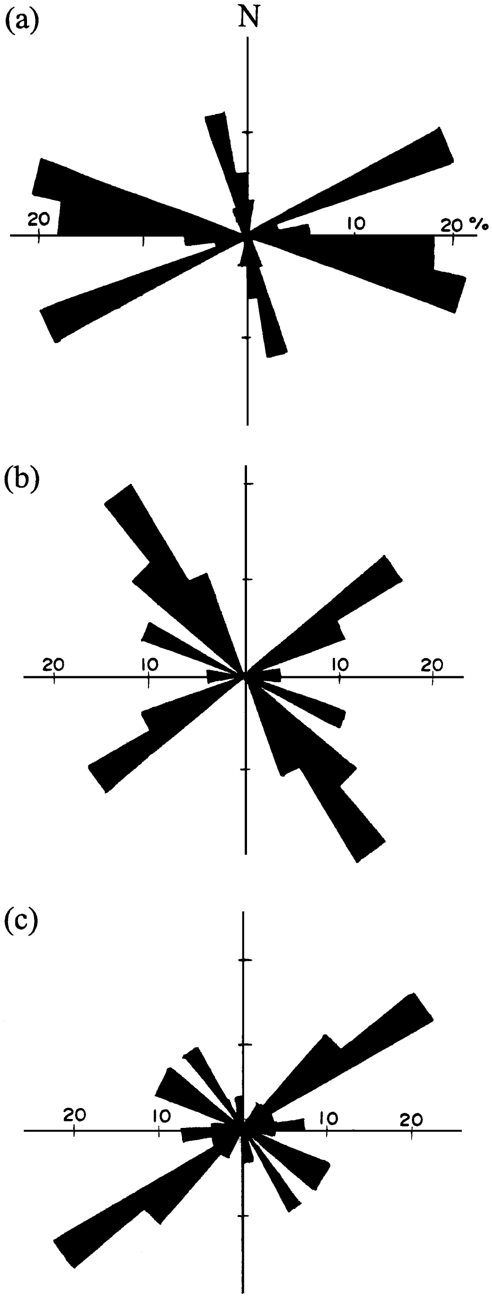

Fig. 7. Rose diagram showing joint systems measured (a) upslope from, (b) at, and (c) downslope from the monocline.

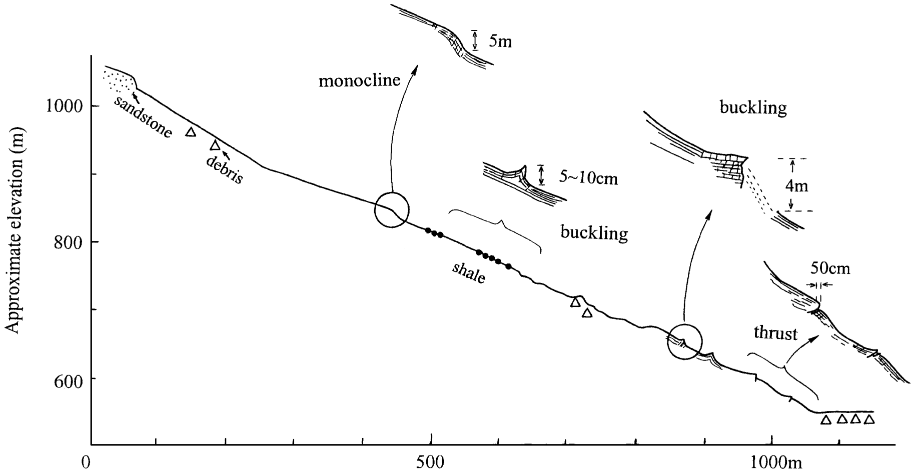

Fig. 8. Measured profile of the Chiu-fen-erh-shan landslide with various features from the buckling of strata.

landslide (Figs. 3 and 4), the steep step is obviously the surface expression of the subsurface deformation that made the monocline (Figs. 3 and 4). Evolution of the monoclinal deformation is depicted in joint orientation and joint filling. Most joints measured on the slip surface strike N50°–70°E, nearly perpendicular to slip direction, as shown in Fig. 7. But the middle limb of the monocline described above has one more set of joint that is prevalent in N30°–40°W, parallel to the slip direction. The joints parallel to the slip direction may have resulted from a gravitational stress, which was unrelated to the earlier folding episode. The nearly EW-striking joints on the slope are often calcite-filled, showing that they were formed from a tectonic stress rather than a gravitational stress. The NW-trending joints are scarcely filled with calcite.

In addition to the monocline described above, small buckling and wedging features were clearly found on the slip surface and the strata beneath it in March 2000 (Figs. 6B,C, 8 and 9). The hinge of the buckling or wedging are up to 10 cm high and have sharp jagged edges, aligned to form a linear feature up to 10 m long. Thrusting with the hanging wall protruding about 50 cm from the slip surface has been found near the toe of the failed slope (Fig. 9C). These small deformational features were formed after the 1999 landslide, as evidenced by their angular edges.

5. Discussion

5.1. The origin of the slip surface

The strata in the studied area are mainly bedded sandstone and shale, which tend to flexural slip during folding (Davis, 1984). The slip surface of the Chiu-fen-erh-shan landslide is parallel to the bedding plane. Such a slip surface is easy to develop along a pre-existing bedding fault that was formed during flexural slip folding in the past. The bedding faults can be found in various horizons and some of them are easily recognized in the landslide scar as well as on its outside. Although the slip surface consists of several bedding faults, it appears very smooth. The clay seams of the bedding faults have the same mineral constituents as the host rocks, indicating that chemical weathering did not prevail in the clay seams as compared with the surrounding host rock.

5.2. Creep and buckling

The monoclinal structure exposed on the upper part of the slip surface indicates that the strata were subjected to creep deformation and had been buckled before the Chi-chi earthquake. Gravitational creep is the slow, imperceptible deformation of slope materials under stresses lower than those required to

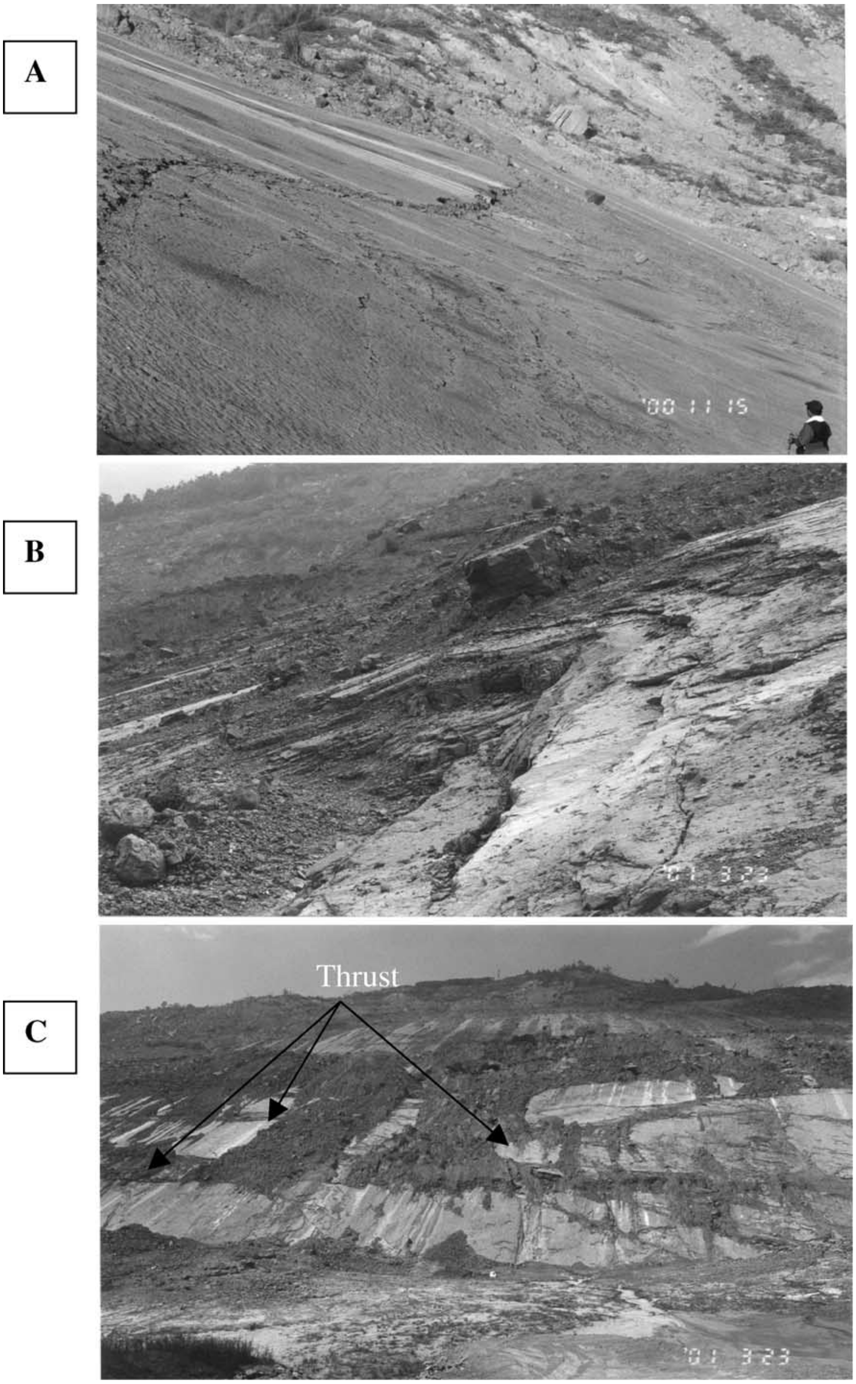

Fig. 9. Deformed features after the 1999 landslide. (A) Large buckling of alternated beds of sandstone and shale with ripples. (B) Small buckling of the strata. (C) Thrust faults in the lower part of the landslide area.

produce sudden failure (Hunt, 1984). Attewell and Farmer (1976) also stated that mass (rock) creep, being controlled mainly by gravity, takes place under stresses that are only a fraction of the peak strength of the material.

Buckling is a kind of typical gravitational deformation in slab-like rock mass, which forms a cataclinal overdip slope and is supported downslope by its toe (Cavers, 1981; Chigira, 1992; Hu and Cruden, 1993). The slope of the Chiu-fen-erh-shan landslide was parallel to the bedding plane, which smoothly curved convex upward (Fig. 3), showing that the upslope beds push the beds downslope away from the center of weight. Therefore, the beds are vulnerable to buckling. In addition, buckling is probably facilitated by the presence of high-angle joints trending NE, as the beds separated by the joints would be bent rather easily. On these conditions, the strata that slid in the 1999 earthquake had crept and were buckled before that event.

The strata that failed during the Chi-chi earthquake had previously crept, but were supported by a 100-m-thick sandstone bed at the foot of the slope, as shown in the A–A′ cross-section of Fig. 3. This was clarified by the detailed geological mapping after the landslide. The sandstone bed has formed resistant protruding ridges at the foot of the slope before the 1999 landslide. This sandstone bed was probably damaged seriously by the Chi-chi earthquake tremor, leading to a catastrophic slide. Similar geological configuration was observed at the Madison slide that occurred in 1959 in the United States (Hadley, 1964, 1978). The upslope of this landslide was composed of schist and gneiss, and the downslope was dolostone, both dipped downslope steeply. Whether creeping occurred or not before sliding is unknown, but the dolostone is inferred to have supported the schist and gneiss upslope. An earthquake (M=7.1), whose epicenter was located 20 km from the landslide site, broke the dolostone and triggered a huge landslide, rockslide, and avalanche, for an estimated volume of 21×10^6 m^3. Loss of support from downslope generally leads to a catastrophe like these cases.

Buckling, wedging, and thrusting similar to those proposed by Hutchinson (1987) occurred more densely in the lower part of the slope than the upper part (Fig. 9) after the 1999 landslide. This is due to the following three factors. Firstly, the bedding-parallel clay seams are present throughout the slope. Secondly, the slope inclination becomes steeper downslope. Finally, the sandstone bed supporting the unstable strata was removed during the 1999 landslide. As indicated by these deformations, the lower part of the slope of the Chiu-fen-erh-shan landslide is currently still creeping, and therefore, susceptible to further sliding. Catastrophic landslide disasters will recur because the failure of the lower slope destabilizes the upper slope.

The short linear depression on top of the dip slope could have resulted from the effect of creeping. Creeping on the hillside can initiate tension cracks, leading to the formation of linear depressions like grabens. Thick-bedded hard rock is often found to creep downslope gradually and widen the gaps between them and the parent ledge (Selby, 1993). Normal faulting generated under the tensile stress field can also form linear depressions. Chigira (1992) has illustrated several examples that creep-induced linear depressions are often found on the top of large creeping areas. The linear depression on the top of the Chiu-fen-erh-shan landslide is postulated to occur under the tensile stress field resulting from downward slipping along the pre-existing clay seams.

Geological structure and the geometrical relationship between beds and slope surface thus provided basic causes for the landslide and had led to the precursory movement. However, the slopes to the southwest of the 1999 landslide area did not show precursory feature, even though they had similar geological structure and geometrical relationship between beds and slope surfaces to those of the landslide area (Figs. 3 and 4). The following two factors are considered to have hindered the slopes southwest of the landslide area from creeping. Firstly, thick sandstone of Chm widely covers and protects the slopes. Secondly, the slopes are farther from the synclinal axis than the landslide area and have gentler bedding dips from 14° to 22° (Fig. 3).

5.3. Drainage pattern and groundwater condition

The long-term creeping loosens rocks which become more permeable. The higher permeability results in higher infiltration capacity and consequently leads to a low drainage density within the creeping area (Higaki, 1996). The high infiltration capacity decreases surface runoff, which erodes land surface to form a gully. Therefore, the low drainage density of 2.5 km^{-1} in the Chiu-fen-erh-shan landslide area is most likely the resultant effect of creeping, and can act as a geomorphological precursor to the slope instability.

The infiltrating rainwater, in turn, was unfavorable to the stability of the slope area. A creek, as indicated by D in Fig. 4, originally provided enough water for living and irrigating a rice field on the middle and low parts of the slid slope before the Chi-chi earthquake. The first author found much flowing water along the slip surface near the trace of this creek 5 days after the 1999 earthquake. The slid slope apparently contained much groundwater unfavorable to its stability.

6. Conclusions

(1) The Chiu-fen-erh-shan landslide occurred on a dip slope. The dip slope is composed of Miocene shale, sandstone, and their interbeds. The dip becomes steeper, from 20° to 36°, toward downslope.

(2) This landslide is located on the western limb of an N–S trending syncline, which resulted from earlier flexural slip folding. The fold axis is about 500 m from the toe of the landslide.

(3) The landslide that occurred along the slip surface developed along pre-existing bedding faults, which resulted from flexural slip folding.

(4) A linear convex slope break and a linear depression appeared on the hillslope as a result of creeping and buckling of strata before the 1999 landslide. Such geomorphological features can be treated as precursors of slope instability.

(5) The low drainage density in the Chiu-fen-erh-shan area is a distinctive phenomenon detected from the aerial photos taken in 1998. This surface feature is likely the result of creep loosening the surface strata.

(6) The creeping of alternating shale and sandstone on the upper part of the slope had been suppressed downslope by a thick bed of sandstone. This footing sandstone was severely damaged during the Chi-chi earthquake and subsequently triggered the notorious Chiu-fen-erh-shan landslide.

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