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Geologic structure, mechanism, and conditions for rock topples on cataclinal slope, Jinchuan, China

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ABSTRACT
Two rock topples with the opposite dip direction, observed in the Ribangliangzi hill and facing the China Provincial Highway S211, are located on the upper stream of the planned dam of Jinchuan Hydropower Station in China. The new site for submerged part of Highway due to reservoir impoundment is designed to be a tunnel crossing the Ribangliangzi hill. However, at this hill, the stratum facing the Dadu River dips southwestward, whereas the stratum facing the Xinzha Gully dips northeastward. Therefore, it’s regarded as an important slope structure that may lead to an occurrence of landslide directly threatening the future tunnel excavation stability and slope stability along the highway. This paper reports for the geologic structures of the overturned strata, formative processes and mechanism for toppling on cataclinal slopes. It was concluded that the toppling on cataclinal slopes was caused by a combination of toppling and sliding. Furthermore, to analyse the conditions for toppling on cataclinal slope, the cantilever beam model was established and analyzed the minimum strata dip angle required for toppling more prone to occur on cataclinal slope and the critical length of rock stratum. The results reveal that the toppling will be more prone to occur on cataclinal slope while the strata dip angle is greater than 60° even if under a very small external force or without the assistance of external forces.

1. Introduction
Toppling as a failure mechanism has been recognized in natural or excavated slopes including road cuts, dam foundations, benches in open pits and natural cliffs. There are many works on toppling concentrated on topples on anclinal slopes
(e.g. De Freitas and Watters 1973; Goodman and Bray 1976; Wyllie 1980; Woodward 1988; Aydan and Kawamoto 1992; Chigira 1992; Adhikary et al. 1996; Nichol et al. 2002) where discontinuities dip into the slopes. However, Lugeon (1933) suggested that toppling also occurred on slopes where discontinuities dip more steeply but in the same direction as the slope. Such slopes, in which the discontinuities dip under the slopes, are called underdip slopes (Cruden 1989). Based on the Goodman and Bray’s kinematic model of common toppling, Cruden (1989) showed that flexural toppling can occur when the discontinuities dip in the same direction as the slope but more steeply than the slope and the angle of friction on the discontinuities. Topples on cataclinal slopes were found in the Bohemian Massif by Rybar and Vrba (1982), in the Highwood Pass in Kananaskis Country, Alberta, Canada by Tang (1986), in the Yellowhead Pass by Cruden (1989) and in the Siwalik Hills, Midwestern Nepal by Tamrakar (2002). Cruden suggested that, with the assumptions of Goodman and Bray (1976), toppling can occur on cataclinal slopes without the assistance of external forces. Cruden (1989) analyzed the control factors of toppling and described the progress of toppling on cataclinal slopes. Tamrakar (2002) revealed a complex rock topple–rock slide structure in the Siwalik Hills and summarized the formative processes and mechanisms.

To find conditions for common toppling on cataclinal slopes, the mechanics of toppling on cataclinal slopes were briefly analyzed by Cruden (1989) based on the same assumptions as Goodman and Bray (1976) made to derive their kinematic criterion for toppling on anacinal slopes. With the assuming that the largest principal compressive stress is parallel to the natural slope and that toppling is initiated by shear along the discontinuities parallel to their dip direction, Cruden (1989) shows that, as $\beta + (90-\psi) > \phi$, toppling is possible on all cataclinal slopes with angles, $\beta$, steeper than the angle of friction, $\phi$, on the penetrative discontinuity, where $\psi$ is the strata dip angle. Therefore, the condition for toppling on cataclinal slopes can be written as $\beta + (90-\psi) > \phi$. However, the analytical solution given by Savage et al. (1985) indicated that the largest principal compressive stress may not parallel to the low angle slopes so that the possibility of toppling under the low angle slope when the discontinuity dips at lower angles down the slope is questionable.

Based on the above analysis, the pre-existing reports indicate that it is probable that the toppling under gravity alone on cataclinal slopes is confined to flexural toppling, whereas block toppling on cataclinal slopes requires assistance. External forces such as water pressure, freezing, and loose materials wedging into discontinuities have all contributed to initiation and development of the block topples.

However, the conditions required for toppling on cataclinal slope, such as the minimum strata dip angle and the critical length of rock stratum, have not been well studied. This paper focus on the study of flexural toppling. Selecting Ribangliangzi hill, where two topples with the opposite dip direction are observed, as a case study. It is regarded as an important slope structure that may lead to an occurrence of landslide directly threatening the future tunnel excavation stability and slope stability along the highway. The purpose of this work is to clarify the geologic structures of the overturned strata, revealing the formative processes and mechanism for toppling on cataclinal slope. Furthermore, to analyze the conditions for toppling on cataclinal
slope, the cantilever beam model was established and analyzed the minimum strata dip angle required for toppling more prone to occur on cataclinal slope and the critical length of rock stratum.

2. Field investigations

Two topples with a total thickness of 160 m, observed in a strip-shaped hill called Ribangliangzi hill and facing the China Provincial Highway S211, were located on the upper stream of the planned dam of Jinchuan Hydropower Station in China (Figures 1 and 2). After the reservoir impoundment, the Provincial Highway S211 will be submerged for six kilometers near the dam site of Jinchuan Hydropower Station. The new road site for submerged part was designed to cross the Ribangliangzi tunnel. However, the presence of two topples is directly threatening the future tunnel excavation stability and slope stability along the highway.

The Ribangliangzi hill was formed by the deep river incisions of Dadu River and Xinzha Gully parallel to each other (Figure 2). It has a length of 5 km approximately and a maximum width less than 800 m. The elevations of the Ribangliangzi hill range from 2160 to 2570 m a.s.l. The slope gradient varies from 40 to 45°.

The stratum is composed mainly of alternating thin-medium layer metamorphic sandstone and carbonaceous phyllite of Zagunao Group in Upper Triassic system. The stratum in the region is constituted of homoclinal structures with a strike of roughly N30°W-N40°W and a southwestward dip. The dip varies from 65° to 70°. Figure 3 is the profile A–A’ trending NE–SW. As shown in Figure 3, the stratum facing the Dadu River dip southwestward, whereas the stratum facing the Xinzha Gully dip northeastward. This means that the slope facing the Dadu River was an anaclinal slope, whereas the slope facing the Xinzha Gully was a cataclinal slope before the
stratum was overturned. However, the strata of adjacent slopes and the underlying strata also dip southwestward.

The stratum facing the Dadu River, that’s a typical toppling structure there is now an extensive international literature related to (De Freitas and Watters 1973; Goodman and Bray 1976; Chigira 1992). However, the northeastward dipping stratum facing the Xinzha Gully was overturned. We inferred that the overturned strata facing the Xinzha Gully might was formed by a forward rotational movement. This phenomenon that toppling occurred on cataclinal slope was firstly found by Lugeon (1933) and also reported by other researcher later (Rybar and Vrba 1982; Tang 1986; Cruden 1989; Tamrakar 2002). It is regarded as an important slope structure that may lead to an occurrence of landslide. Therefore, it is necessary to clarify its structural details for the evaluation of future tunnel excavation instability and slope instability along the highway.

Figure 2. Topography and distribution of two topples in Ribangliangzi hill: 1 the stratum of Zagunao Group in Upper Triassic system; 2 boundary of topples; 3 pre-existing Highway S211; 4 new road site for submerged part after the reservoir impoundment; 5 country road; 6 profile A-A; 7 planned dam; 8 exploration adit; 9 river; 10 contour line.

Figure 3. Toppled structure in geological profile A-A’ (profile location is shown in Figure 2): 1 alluvium; 2 alternating thin-medium layer metamorphic sandstone and carbonaceous phyllite; 3 Quaternary; 4 the stratum of Zagunao Group in Upper Triassic system; 5 boundary of topples; 6 exploration adit; 7 profile direction.
3. Geologic structures of the overturned strata

Figure 2 is a detailed topographic and geologic map based on the field surveys. One of topples shown in Figure 2 is a west-facing slope, it is defined as topple (T₁). Another topple east-facing slope, it is defined as topple (T₂). Two topples totally cover an area of 5000 m². Both the topple (T₁) and topple (T₂) traced northwestward, as indicated by the broken line in Figure 2. The dip direction of stratums between two topples differs and their strikes were almost the same. The boundary between normal and overturned strata, which exhibits a smooth curve approximately parallel to the slope surface, and is indicated by the broken line in Figure 3. Characteristics and geologic structures of two topples were described in the following paragraph.

The elevation of Topple (T₁) ranges from 2160 to 2500 m a.s.l. The shallow rock masses were broken attributed to strongly toppling with the strata dip angle varying from 10° to 35°. The exploration adit (TPD₂) showed that the horizontal width of toppling was approximately 130 m (Figure 3). However, the continuous toppling fracture surface was not observed based on the exploration adit TPD₂.

Topple (T₂) was located at the west bank of the Xinzha Gully. The width of the overturned rock mass measured along adit TPD₁ is 25 to 30 m in the profile A–A’ (Figure 3). Part of field area is shown in Figure 4. The lower boundary between normal and overturned strata was exposed at the gully at the 2210 m a.s.l. The upper boundary extended to the slope shoulder at the 2500 m a.s.l. According to the exploration adit TPD₁, the dip angle of overturned stratumm varies from 15° to 28° within the horizontal distance of 30 m from the slope surface, and then gradually increasing with the increase of distance to the slope surface. The dip angle approximately would be a normal range while the horizontal distance is greater than 30 m.

In conclusion, it can be found that two topples have similar characteristics, such as a uniform slope gradient varying from 40° to 45°, the same lithology and the same stratum...
The dip angle of overturned mass. However, the horizontal width of toppling in an acnal slope is much larger than that in cataclinal slope. The boundary between normal and overturned strata was approximately parallel to the slope surface. Although the dip direction between the strata of topple $T_1$ and topple $T_2$ differed, their strikes were almost the same. The rock mass was broken obviously with poor integrity. However, the continuous toppling fracture surface was not identified in the exploration adits.

4. Toppling processes and mechanism on cataclinal slope

Lugeon (1933) suggested that toppling also occurred on slopes where discontinuities dip more steeply but in the same direction as the slope. Cruden suggested that, with the assumptions of Goodman and Bray (1976), toppling can occur on cataclinal slopes without the assistance of external forces.

The present example is a case of topple structures exposed in a narrow strip-shaped hill. Based on the above analysis of geologic structure, obviously, the stratum facing the Dadu River with discontinuities dip into the slope, tends to be susceptible to toppling due to gravity. There are many works on toppling concentrated on topples on anacanal slopes (De Freitas and Watters 1973; Goodman and Bray 1976; Woodward 1988; Chigira 1992; Nichol et al. 2002). Hence, this study focuses on the processes and mechanism of toppling on cataclinal slopes instead of anacanal slopes.

However, the strata facing the Xinzha Gully and dipping downslope, is relatively more difficult to topple under gravity alone.

Therefore, to better understand the processes and mechanisms of toppling on cataclinal slopes, four favourable geological conditions for toppling occurring on cataclinal slopes are discussed in the following discussion.

1) Particular topography

Ribangliangzi hill was formed by the deep river incisions of Dadu River and Xinzha Gully parallel to each other (Figure 2). The toppling on cataclinal slopes is more likely to happen in this particular topography with three free surface. This feature is likely to have caused a different stress pattern in the slope of study area compared to the other wider valleys only with single free surface, which might be favoured to the rock mass unloading and relaxation facilitating the toppling (Panizza 1973).

2) High contrast in strength between strata

The stratum is composed of a high proportion of metamorphic sandstone with carbonaceous phyllite in alternating sequence of Zagunao Group in Upper Triassic system. It’s characteristics of a high contrast in strength between metamorphic sandstone and carbonaceous phyllite (You 2013). Due to the high proportion of carbonaceous phyllite in this area, shearing may tend to occur along the bedding planes between the interface of metamorphic sandstone and carbonaceous phyllite, and also tend to occurred along cleavage of carbonaceous phyllite.

3) Steeply dipping strata

The toppling on cataclinal slopes is more likely to happen in the steep slope. Cruden and Hu (1994) described the topples on underdip slopes at 16 sites and revealed that the average dip of toppled beds is greater than 55°. In the study area,
the outcropped lithology is in alternating sequence of hard and soft rock with the stratum dip varying from $65^\circ$ to $70^\circ$, which is favourable to toppling.

4) Rapid river dissection at the foot of the slope

The highest river terraces along the Dadu River range in elevation from 340 to 494 m a.s.l. (Liu 2006). This means that this area is an uplifted zone that has been under river dissection since the early Pleistocene. Steep slopes facing the river indicate that rapid dissection continues. Therefore, the toppling have occurred after the early Pleistocene.

Based on the above analysis, it is concluded that the formation of the toppling on cataclinal slopes are discussed in the following two stages.

5) Initial deformation stage

Based on the regional tectonic data, the study area is an uplifted zone that has been under River dissection since the early Pleistocene (Liu 2006). Firstly, the slope stress field distribution has been altered in the process of river incision. The occurrence of unloading was caused by release of the lateral support of the slope. Therefore, the tensile stress concentration was mainly distributed at the rear part of slope and the shear stress concentration was distributed at the toe of slope. The rock mass relaxation, cracking and dislocation along the schistosity of carbonaceous phyllite were caused due to release of lateral support of the slope in the process of river incision [Figure 5(a)]. Secondly, based on the reports by Cruden who showed that toppling can occur on cataclinal slopes without the assistance of external forces with the assumptions of Goodman and Bray (1976), we conclude that the initial toppling might occurred at the toe under the principal compressive stress parallel to the slope surface [Figure 5(a)], or other external forces such as horizontal seismic force or hydrostatic pressure. Moreover, there may be no rapid mass movement and the bedding layers have been gradually folded during toppling (Cruden and Hu 1994).

6) Toppling-sliding stage

Due to the high contrast in strength between metamorphic sandstone and carbonaceous phyllite, the slip occurred at the upper part of slope along the bedding planes between the interface of metamorphic sandstone and carbonaceous phyllite, and the cleavages of phyllite [Figure 5(b)]. With the development of slip, the bedding joints at the lower part of slope begin to bend toward to the free surface due to constraints of riverbed, and then gradually toppling from bottom to top [Figure 5(c)].
Both good condition of free face at the toe and the long-term strength degeneration of the thin layer carbonaceous phyllite due to river erosion greatly facilitated the toppling of slope. Once the bending of toppling reaches to a limit value, it will generate the discontinuous fracture surfaces within rock mass. If there are structural planes or small faults which dip in the same direction as the slope, the toppling failure surface will be prone to trace these discontinuities. While these fracture surface of each adjacent bedding joints are linked together, the continuous failure surfaces will be generated within rock mass [Figure 5(d)].

In conclusion, it’s possible that an overall catastrophic failure due to toppling-sliding occurs in this slope structure just similar to the Ribangliangzi hill. Consequently, it is concluded that the toppling on cataclinal slopes in Ribangliangzi hill was caused by a combination of toppling and sliding.

5. Conditions for toppling on cataclinal slope

In order to analyse the conditions for toppling on cataclinal slope, the cantilever beam model was established and analysed the minimum strata dip angle required for toppling more prone to occur on cataclinal slope as well as the critical length of rock stratum. The cantilever beam model OA is presented in Figure 6. Parameters are defined as follow: $x$. Horizontal axis for beam; $y$. Vertical axis for beam; $b$. Thickness of beam; $h$. Height of beam; $\gamma$. Unit weight of beam; $l$. the length of beam; $\alpha$. the stratum dip angle. The lateral force acting on beam is assumed to be a linear distribution. The shear force between beams is assumed to be zero.

The $\varepsilon$ is the beam end deflection. When the value of $\varepsilon$ is greater than zero ($\varepsilon > 0$), and the beam will bend toward the same direction of the y-axis. Therefore, the following analysis focuses on that when the value of $\varepsilon$ is assumed to be greater than zero ($\varepsilon > 0$). Namely, the toppling is assumed to occur on cataclinal slope, and conditions required for toppling are demonstrated as follows.

Self-weight is decomposed into the horizontal force $q_1$ along the X axis direction and the vertical force $q_2$ along the Y axis direction. It is found as follows:
\[ q_1 = bl_\gamma \sin \alpha \]  
\[ q_2 = bl_\gamma \cos \alpha \]  

And the linear distribution function of the lateral force can be expressed as:

\[ q(x) = q - \frac{q_1}{x} \]  

The \( \nu \) is defined as the bending deflection of beam, the geometric boundary and the mechanical boundary can be written as:

\[ \nu_{x=0} = 0 \]
\[ \nu_{x=l} = \varepsilon \]
\[ \nu_{x=0} = 0 \]

The equation of deflection curve can be written:

\[ \nu = \varepsilon \left(1 - \cos \left(\frac{\pi x}{2l}\right)\right) \]  

The strain energy can be written:

\[ U = \frac{EI\varepsilon^2\pi^4}{64l^3} \]  

where \( E \) is the elastic modulus and \( I \) is the moment of inertia.

Therefore, the works done by the lateral load \( q \) can be expressed as follows:

\[ W_1 = \int_0^l \nu q(x)dx = \varepsilon \int_0^l \left(1 - \cos \left(\frac{\pi x}{2l}\right)\right) \left(q - \frac{q_1}{x} x - q_2\right)dx 
= \varepsilon \left(\frac{ql}{2} - q_2l + \frac{2l}{\pi} q_2 - \frac{4ql}{\pi^2}\right) = \varepsilon (0.095ql - 0.363q_2l) \]  

And, the work due to the axial displacement can be obtained:

\[ W_2 = q_1 \int_0^l \int_0^l \frac{1}{2} \left(\frac{d\nu}{dx}\right)^2 dxdx = \frac{1}{32} \pi^2 \left(1 - \frac{4}{\pi^2}\right) q_1 \varepsilon^2 = 0.183q_1\varepsilon^2 \]  

The total potential energy while the bending occurring in the bedding plane can be written as: \( \Pi = U - W_1 - W_2 \)

Based on the minimum potential principle \( \frac{\partial \Pi}{\partial \varepsilon} = 0 \), it’s found as follows:

\[ \frac{EI\pi^4}{32l^5} \varepsilon - 0.095ql + 0.363q_2l - 0.366q_1\varepsilon = 0 \]  

where, \( I = \frac{lb^3}{12} \)
Only the small deflections and the small rotating angle are discussed in mechanics of materials. Therefore, the value of \( W_2 \) is very small and can be negligible. The critical length \( l \) required for beam bending toward the same direction of the y-axis \((\varepsilon > 0)\) can be obtained:

\[
l = \sqrt[3]{\frac{Eh^2\pi^4\sin \alpha}{36.48q - 139.392q_2}} \varepsilon
\]

When the length of beam is greater than the critical length \( l \), it is possible that the bending toward the Y axis direction occurs. Therefore, the above analyses demonstrate that the toppling possibly occurs on the cataclinal slope, when the length of rock stratum is greater than the critical length \( l \).

When the value of the lateral load \( q \) is quite small, namely, \( q = 0 \), according to Equation (8), the critical length \( l \) decreases with the increase of the stratum dip angle \( \alpha \). Therefore, when the stratum is up-right, namely, \( \alpha = 90^\circ \), the minimum critical length \( l' \) can be obtained:

\[
\frac{Ehb^3\pi^4}{384} \varepsilon - 0.363q_2l - 0.366q_1\varepsilon = 0 \iff \frac{Ehb^3\pi^4}{384l^3} \varepsilon - 0.363bl'\gamma \cos \alpha l - 0.366bl'\gamma \sin \alpha \varepsilon = 0
\]

\[
\iff \frac{Ehb^3\pi^4}{384l^3} \varepsilon - 0.366bl'\gamma \varepsilon = 0 \iff l' = \sqrt[3]{\frac{Eb^2\pi^4}{140.544\gamma}}
\]

When the value of the lateral force is quite small, it can be written as:

\[
\lim_{q \to 0} \frac{Eh\pi^4}{32l^3} \varepsilon - 0.095ql + 0.363q_2l - 0.366q_1\varepsilon = 0 \iff \frac{Eh\pi^4}{32l^3} \varepsilon + 0.363q_2l - 0.366q_1\varepsilon = 0
\]

In order to verify the Equation (12), taking cantilever beam element for analysis. With the assuming that the largest principal compressive stress is parallel to the...
natural slope. Considering the effect of shearing force, the force analysis diagram is as shown in Figure 7.

According to the force balance analysis, one obtains

\[ \sigma_n = \frac{\sigma_h - \sigma_v \cot^2 \alpha}{1 - \cot^2 \alpha} \]  

Substituting Equation (13) into Equation (14), \( h = l \sin \alpha \), one gets

\[ \sigma_n = \frac{0.00903 l \sin \alpha - 0.0271 l \sin \alpha \cot^2 \alpha}{1 - \cot^2 \alpha} \]

Based on the above analysis, it can be obtained that the lateral force \( q \) is \( b \sigma_n \) while the length of beam is \( l \), namely, \( q = b \sigma_n \).

To make the toppling occurs on the cataclinal slope, namely, \( q > 0 \), it can be expressed as:

\[ 0.00903 \sin \alpha - 0.0271 \sin \alpha \cot^2 \alpha > 0 \]
\[ 1 - \cot^2 \alpha > 0 \]
\[ \iff \alpha > 60^\circ \]

Combining the Equation (12) with Equation (16), it reveals that the toppling will be more prone to occur on cataclinal slope while the strata dip angle is greater than 60° even if under a very small lateral force or without the assistance of external forces. In conclusion, the critical length of rock stratum required for toppling on the cataclinal slope was derived as follows:

\[ l = \sqrt{\frac{E b^3 \pi^4 \sin \alpha}{36.48q - 139.392q_2}} \]

When the stratum is up-right, namely, \( \alpha = 90^\circ \), the minimum critical length \( l' \) can be obtained as follows:
6. Conclusion

In this research, two rock topples on the upper stream of the planned dam of Jinchuan Hydropower Station in China was investigated and analyzed the geological structure, formative processes, mechanism and condition for toppling occurring on cataclinal slope.

The causes for toppling on cataclinal slopes include: (1) particular topography, formed by the deep river incisions of Dadu River and Xinzha Gully parallel to each other; (2) steeply dipping strata; (3) a high proportion of carbonaceous phyllite to metamorphic sandstone, (4) a high contrast in strength between carbonaceous phyllite to metamorphic sandstone, and (5) rapid river dissection at the foot of the slope. The initial toppling might occurred at the toe under the principal compressive stress parallel to the slope surface, or other external forces such as horizontal seismic force or hydrostatic pressure. There is a good agreement with the viewpoint of Goodman and Bray (1976).

The cantilever beam model was established and analyzed the minimum strata dip angle required for toppling prone to occur on cataclinal slope and the critical length of rock stratum. It reveals that the toppling will be more prone to occur on cataclinal slope while the strata dip angle is greater than 60° even if under a very small external force or without the assistance of external forces. The critical length of rock stratum $l$ is derived as shown in Equation (9) and the minimum critical length $l'$ is obtained as shown in Equation (10) while the stratum is up-right ($\alpha = 90^\circ$).

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Disclosure statement

No potential conflict of interest was reported by the authors.

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