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ORIGINAL PAPER

Significance of outward dipping strata in argillaceous limestones in the area of the Three Gorges reservoir, China

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Abstract Re-location of the town of Fengjie due to the impounding of the Three Gorges reservoir involved some significant excavations into the valley slopes. It was noted that the mainly calcareous strata in gullies had a northerly dip while in the excavation the dips were sub-horizontal and even southerly, towards the Yangtze River. The paper discusses the process which leads to this change in dip in the superficial strata. This is particularly significant where orthogonal sub-vertical discontinuities are present such that gravitational effects result in blocks toppling out of the free face.

Keywords Slope stability · Calcareous strata · Toppling · Deep excavations · Three Gorges · Fengjie

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Introduction

As a consequence of the construction of the Three Gorges Dam, much of the area upstream will be flooded by the large reservoir which will be impounded to an elevation of 175 m asl and extend some 600 km upstream of the dam (Fig. 1). As a result, the town of Fengjie, which initially was at the confluence of the Mixihe and Yangtze Rivers, was re-located some 4 km upstream of the old site, again on the north bank of the Yangtze River.

The re-development of the site for the new town involved the building of much infrastructure as well as a new highway along the northern slope of the valley. In several places this necessitated excavation into the steep rock slopes. Figure 2 shows the position of one of these excavations, adjacent to the Yufu gas station slope.

The paper describes the geology of the area and the significance of the interbedded marl bands within the general limestone/sandstone succession. These argillaceous strata have experienced weathering and creep movement which has affected the dip near the natural hill slopes, such that toppling failure occurs.

Geology

The main strata exposed in Fengjie County are members of the Badong Formation of tertiary age (Team 107 of Geological Bureau of Sichuan province 1980). Four members of the Badong Formation are present.

The oldest member (T_2b^1) begins with medium to thickly bedded grey and dark grey dolomitic limestone, changing upwards to a mainly yellow grey mudstone and shale. The strata outcrop adjacent to the Yangtze River and

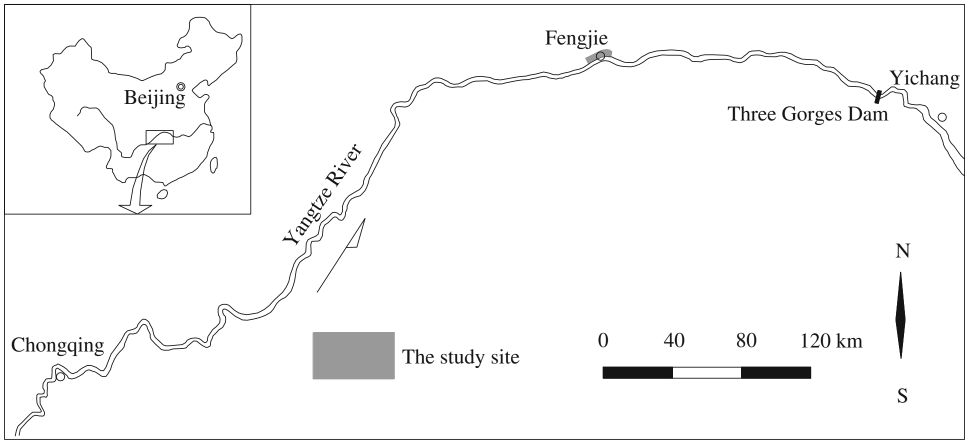

Fig. 1 The location of the study site

Fig. 2 The topographic feature of Yufu gas station slope

will be flooded after the reservoir is impounded to 175 m asl (see Fig. 3).

The second member (T_2b^2) has a thickness of 100–241 m and consists mainly of purple red mudstone intercalated with variable thicknesses of silty sandstone and calcareous sandstone. In the studied site, these strata mainly outcrop in the bank slope of the Yangtze River, usually below some 150 m asl except in the Kouqian area. In the bank slopes of the Meixihe River, the member mainly outcrops below 140 m asl (see Fig. 3). Most of this area will be flooded after the reservoir is impounded.

The third member (T_2b^3) has a thickness of over 300 m and can be conveniently divided into two parts. The lower part (approximately 200–240 m thick) consists of grey to dark grey limestones/argillaceous limestones intercalated with mudrocks and marls. The upper part consists of grey

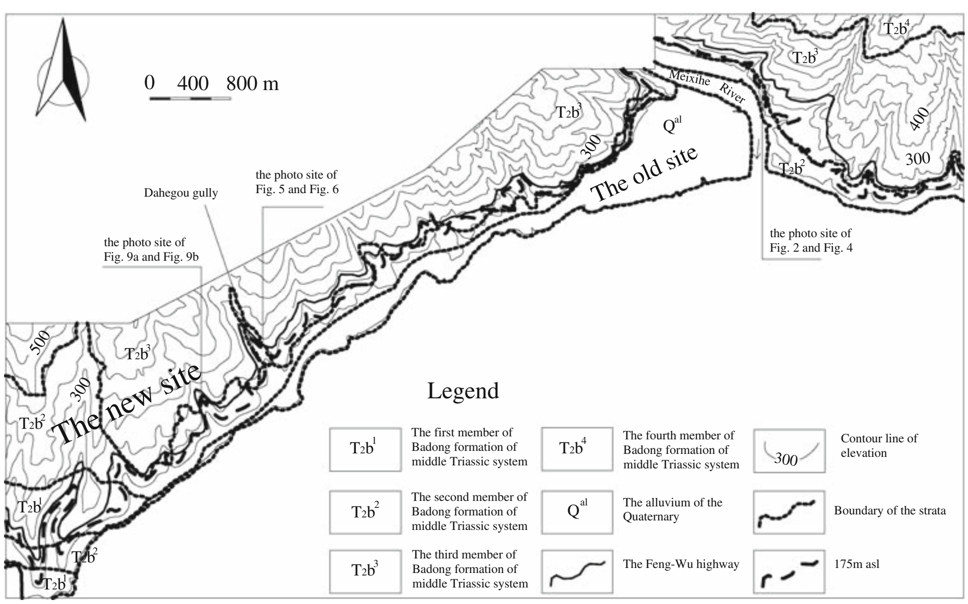

Fig. 3 Geological map of the Fengjie County area (revised after Qi et al. 2009)

thin to medium bedded argillaceous limestones and marls interbedded with purple red and grey/green calcareous silty sandstones and mudrocks. These strata outcrop over much of the studied site (see Fig. 3). Almost all re-located buildings of the new County and new towns as well as the main highways are founded on these strata.

The fourth member (T_2b^4) has a thickness of some 110 m. It consists mainly of purple red mudstone with medium to thick bedding. Some argillaceous limestone with intercalated calcareous shale is also present. The strata mainly outcrop to the north of the studied site, further from the Yangtze River (see Fig. 3).

As noted above, the succession is an interbedded limestone, calcareous mudrock and calcareous sandstone, all of which are subject to dissolution of the calcite content. This has a major effect on the degree of weathering, which influences the near surface dips and the engineering parameters.

Study area

Two areas where it was necessary to excavate into the strata to form the new highway have been studied: the Yufu gas station slope and the Dahegou slope.

Yufu gas station slope

This area is situated to the east of the Xiayaowan gully which is incised into the hillside to a depth of 40–50 m. Here, the orientation of the slope is almost E–W, and the average natural slope angle is about 34°. The strata strike approximately parallel to the free face of the valley side and dip northwards at 6°–10°, i.e. into the slope. The strata are brown yellow to grey argillaceous limestone with thin to medium beds (0.1–0.5 m). Overlying the bedrock is a thin residual soil/hill wash formed during the progressive development of the Yangtze River valley (see Fig. 2).

When the excavation was undertaken for the construction of the highway, it was found that many of the near surface rocks dip to the south, almost as if the strata were part of an anticline. As seen in Fig. 2, there are extensive, near-vertical fractures in the strata, which pose a potential problem for the long term stability of the cut slope. Many of these near-vertical discontinuities have a veneer of calcareous dripstone, indicating past dissolution of the calcite content in the strata and re-precipitation of this material in the joint system.

The joint system has been measured and found to have an orthogonal shape. In this interbedded sequence, the joints extend vertically for 3–5 m through the stronger limestone beds with an orientation of approximately 220°–250° (Set A) and 300°–330° (Set B), although the lower and upper beds may have a slightly different trend. The discontinuities of Set A have a spacing of 0.3–0.5 m and an aperture of 5–10 mm while those in Set B extend for some 1.5–5 m vertically with a spacing of 0.3–0.8 m and an aperture of 8–15 mm. As a consequence of this joint system, the face appears to be formed of various blocks (Fig. 4a, b).

When the dip of the strata in the original valley side is compared with those in the lower part of the Xiayaowan gully, it can be seen that it changes from a northerly dip in the unweathered bedrock to a pronounced southerly dip near the original valley side. As a consequence of the excavation, a slide occurred, extending through the residual soil/hillwash into the gently outward-dipping strata.

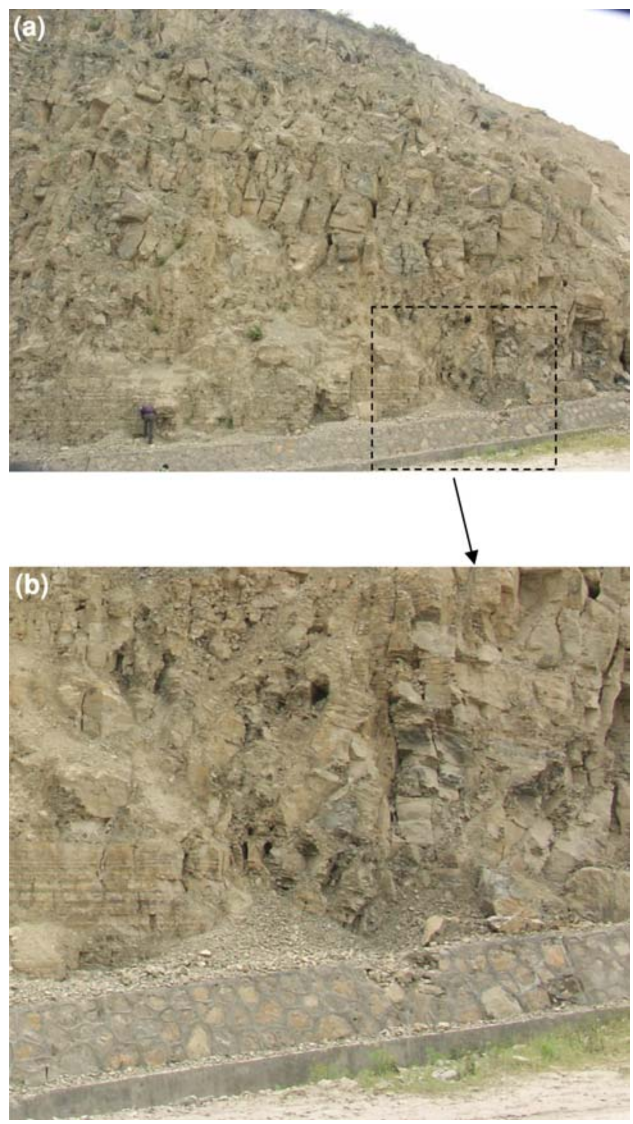

Fig. 4 **a** The outward rotating of the strata and the toppled blocks of the Yufu gas station (the *dash square* in the Fig. 2). **b** The outward dipping strata of the Yufu gas station (the *dash square* in the Fig. 4a)

The Dahegou slope

This slope is on the eastern side of the Dahegou gully, which is incised to a depth of more than 200 m (see Fig. 3). The strata in this area consist of medium to thickly bedded (>1 m) grey yellow argillaceous limestone, part of the T_2b^3 member. Again, the slope face strikes E–W with an average natural slope angle of 28°. When the strata are examined in the gully, the bedrock dips slightly to the north. Figure 5 indicates that in the near surface strata exposed by the excavation for the highway, the rock dips to the south with an angle of over 30° (opposite to the underlying bedrock). The discontinuities seen in the excavated face are well shown in the figure. During the work, some of the discontinuity-bounded blocks fell out, leaving large hollows in the face (Fig. 6).

In both cuttings it is obvious that the strata dips in the valley sides along the Yangtze River are very different near the slope face compared with that in the deep bedrock. It was noted that:

1. The outward-dipping strata only occur in the area where argillaceous limestones are present.
2. The rock mass was dissected into a number of blocks by sub-vertical orthogonal discontinuities.
3. Where the strata dip outwards, the weathering profile is much thicker, indicating a long term disturbance associated with the incision by the Yangtze River.

Discussion

Li et al. (2001) considered that the Yangtze River has been developing since between the Early and Late Pleistocene (i.e. some 1.16 m years BP).

The fresh to slightly weathered argillaceous limestones of member T_2b^3 have a CaO content varying between 46.64 and 53.1% and a maximum $CaCO_3$ content of over 91% (Zhang and Qu 2005; Zhang 2004; Liu 2007). The general groundwater in the area has a pH of 6.17 and hence readily dissolves the calcium carbonate (Zhang 2005). As most of the rocks are calcareous, calcite dissolution has taken place as the Yangtze River has progressively incised, lowering the ground water level. This environmental change has a dramatic effect on the weathering of the strata in both the removal of the calcareous content and the weakening/softening of the mudrocks, such that squeezing and creep movement takes place in these weaker materials.

Fig. 5 The topography of Dahegou slope

Fig. 6 The outward rotating of the horizontal bedding planes and the toppled blocks (the *dash square* surrounded area in the Fig. 5)

The shear strength of calcareous mudrocks has been shown to change significantly as the calcite is removed (Hawkins et al. 1988; Hawkins and McDonald 1992). As a consequence, in the unweathered bedrock, peak shear strengths in the order of 28° are common while with weathering the shear strength of these strata decreases such that the critical strength is 15°–18° with a residual strength as low as 8°–12°; indeed even lower figures have been measured. The significance of this change in shear strength is that in steep slopes with high overburden pressures, the progressively weakened mudrock horizons are squeezed out towards the natural slope face such that the thick limestone bands lose their original support and their dip angle is reduced. The fine grained mudrocks which are squeezed out from the thicker limestone horizons accumulate at the surface of the slope, forming a thick veneer.

In addition to the weathering/outward squeezing of the mudrock horizons, the argillaceous limestones also change in character as the calcium carbonate is dissolved. Figure 7 shows the relationship between the unconfined compressive strength and the calcite content of various samples taken from the cut face. The regression line is UCS = 5.7638EXP(0.0314P) with a correlation coefficient of 0.8890, where *P* is the percentage calcite. Figure 8

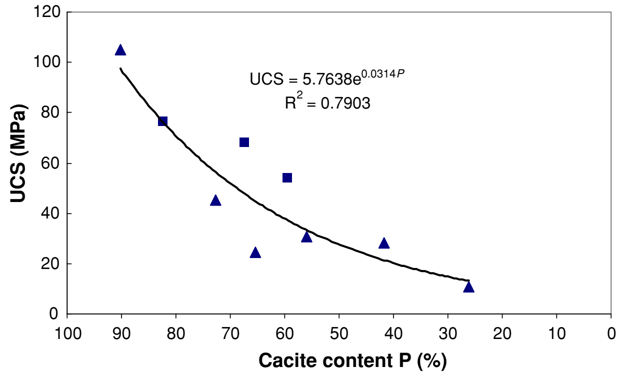

Fig. 7 Calcite content *P* (%) versus UCS (MPa) (note: the data marked with *triangles* is after Zhang 2004 and the data marked with *squares* is after Liu 2007)

shows a similar change in the modulus (E_o) where $E_o = 0.8019EXP(0.0345P)$ with a correlation coefficient of 0.8679. These modifications in the engineering parameters of the strata indicate that with dissolution/time, the thicker rock bands are less able to support the heavy overburden of the upslope strata. As a consequence, the rocks are further fractured and the dip of the strata modified.

Whilst this process is taking place throughout the Yangtze valley where the strata are dominantly calcareous with some interbedded mudstones, in the study area it is particularly important as the excavation for the new highway was cut at angles of 70°–90°. At that time it was not appreciated that the near surface angle of the bedding was much lower than that seen in the outcrops in the gullies and hence the potential for problems was not expected.

The instabilities observed in the cut result from the blocky nature of the strata and the horizontal/southerly dip. In this situation, the gravitation force from the centroid of the block may extend beyond the lower edge of the block such that it becomes unstable and topples. Initially, toppling of the blocks may be inhibited by the frictional forces between the rear of the block and the blocks behind. However, with time, the growth of tree roots etc., the blocks move progressively outwards towards the free face and topple unless restrained.

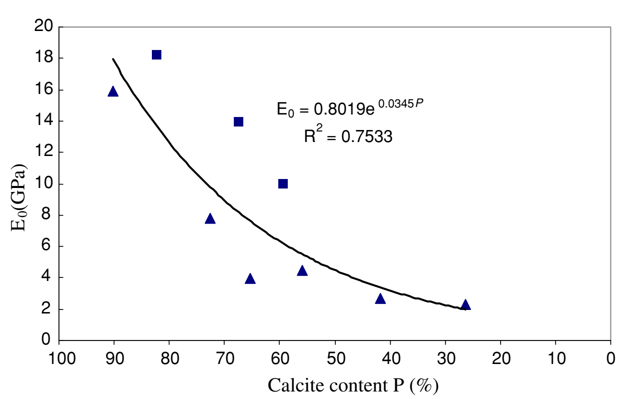

Fig. 8 Calcite content *P* (%) versus deformation moduli of E_o (MPa) (note: the data marked with *triangles* is after Zhang 2004 and the data marked with *squares* is after Liu 2007)

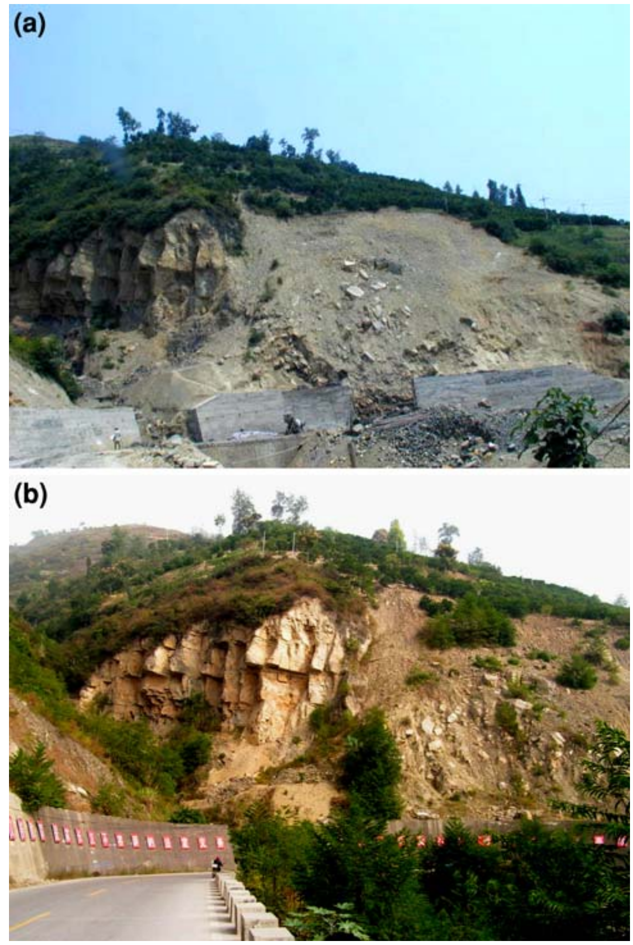

Fig. 9 **a** The slope failure induced by excavation occurred in the Feng-Wu highway (see Fig. 3), **b** The slope supported by a retaining wall

Remedial works

In order to stabilize cut slopes in outward dipping strata and prevent slope failure, commonly used measures include a retaining wall, netting or anchors/bolts. Experience show that a retaining wall is usually more effective than anchors/bolts or netting as it inhibits initial movement of the whole slope face. Figure 9a shows instability in a cut slope with outward dipping strata and Fig. 9b shows the slope after reinforcement with a retaining wall.

Summary and Conclusions

In the area of the new Fengjie town, the strata are calcareous-rich, formed of interbedded limestones/sandstones and mudrocks. The natural slope of the Yangtze River is steepest where the limestones and sandstones are present and hence a number of steep spurs develop between deep gullies.

When the dip of the strata is examined in the deep gullies, it is apparent that it is towards the north. When the strata were exposed during the excavation for the new highway, however, it was noted that the near surface strata were often sub-horizontal or even to the south, i.e. outward dipping.

The Yangtze River valley has been forming for at least a million years. With the progressive incision, changing ground water level and dissolution of the calcium carbonate content of the strata, the geotechnical parameters of both the mudrocks and the argillaceous limestones have been significantly modified. The partially de-calcified mudstones have lower shear strengths and, with progressive weakening/softening, are prone to creep movement due to the heavy overburden pressure. As a consequence, they are squeezed out such that the thick limestone bands drop, changing their dip.

Calcium carbonate is also dissolved out of the argillaceous limestones resulting in a drop in their UCS and E_o values. The reduction in these parameters in a situation where there is a high overburden stress has resulted in further fracturing of the strata.

The thickly bedded, impure limestone blocks have been observed to fall/topple out from the face. This process will continue to develop with time as:

1. the frictional resistance between the blocks at the face and the strata behind is reduced and/or
2. the weaker mudstones/clays are squeezed out of the face, thus reducing the support to the limestone so that the blocks topple forwards.

In view of the natural surface veneer/hillwash material which commonly covers a valley side, it is often difficult to evaluate the potential for toppling failure as the near surface strata dips cannot be observed. Although the dips can be measured in a borehole core, unless downhole geophysics/photography is undertaken the orientation of the dip relative to the free face may not be appreciated.

Experience shows that a gravity retaining wall constructed to provide adequate passive resistance may effectively overcome the forces pushing the strata outward. Where higher forces are considered, the restraining capacity of the retaining walls can be increased by anchoring.

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