Study on the genesis mechanism of structure traces of argillized seams in the engineering slopes at a hydroelectric station in Southwest of China

YUN-JIANG CAO [1], RUN-QIU HUANG [2], TAO FENG [3], HUI LV [4] & HAI-JUN ZHENG [5]

[1] *School of Civil Engineering of Hunan University of Science and Technology, China. (email: caoyj-xt@sohu.com). National Laboratory of Geohazard Prevention and Geoenvironment Protection of Chengdu University of Technology, China. (Email: caoyj-xt@sohu.com)*
[2] *National Laboratory of Geohazard Prevention and Geoenvironment Protection of Chengdu University of Technology, China. (Email: hrq@cdut.edu.cn)*
[3] *School of Civil Engineering of Hunan University of Science and Technology,China. (Email: t feng@hnust.edu.cn)*
[4] *National Laboratory of Geohazard Prevention and Geoenvironment Protection of Chengdu University of Technology, China. (Email: lvhui_0419@ yahoo.com.cn)*
[5] *National Laboratory of Geohazard Prevention and Geoenvironment Protection of Chengdu University of Technology, China. (Email: duoduo5780@ 163.com)*

Abstract: Affected by the ancient geographical environment, the stratum in the engineering area belongs to a set of flysch-type sedimentary formations. The stability of an excavated slope is controlled by many factors, such as strata, synclinal structure and the local geography. The proportion of soft rocks to hard rocks is 30%:70% and four kinds of the typical formations are classified among the soft rock zones. The structure of the rock mass is affected by the slip rupture zones and fault rupture zones in the rock slope. Being the weakest belts in the rupture zones, argillized seams reduce the stability of the slope to some degree, leading directly to time-dependent deformation of the single slope. Owing to repeated intense structural compression, continuous weathering and groundwater percolation later in the original rock of coal seams, complicated argillized seams formations were formed that were developed in shearing rupture zone and zonally distributed in space. The average proportions of argillized and coal seams, carbonaceous shale, and argillaceous siltstone formation in the strata sections are 7.2%, 8.6%, 30.2%, and 54.0% respectively and the argillized seams range from 1.77% to 27.21%. Four different formation stages are proposed for the formation mechanism of the argillized seams. X-ray diffraction analysis tests indicate that there are new clay minerals in the argillized seams in the dam area, identified as illite, kaolinite, chlorite in the proportions 1:0.8:0.6.

Résumé: La région des travaux est limitée par l'envirenement géologique . Il est la formation du sédimnt de flych. La stabilité de déblai du clivus est contrôlée par le lithotype de la strate, la texture du synclinal et la géomorphologie etc. La proportion de la roche dure et souple est de 3 :7. La bande de roche souple se développe à quatre stratums typiques. La zone fracturée de cisaillement entre les couches du corps de la roche de talus, la zone fracturée de la faille influence directement la structure du corps de roche de talus. Les couches intercalées argileuse sont la bande souple de la zone fracturée. Il constitue le danger caché de la différente stabilité pour la stabilité de roche du talus. Même il conduit à la déformation de vieillissement du talus monomère. La roche-mère de la strate de la soute à charbon est passée fortement l'extrudage et le rodage. A cause de la désagrégation vive et de l'osmose continue de l'eau souterraine, il forme la strate de la couche intercalée argileuse complexe. Sa proportion est grande du 1.77% au 27.21%. dont la proportion de la roche argileuse, du schiste charbonneux, de la batture et de la pelite est respectivement de 7.2%, 8.6%, 30.2% et 54.0%. Et on a posé quatre périodes différentes de formation. Pour la période différente de formation, on a fait l'essai de la diffraction de poutre et de cristal de rayon X. On a confirmé qu'il contient l'argile, l'illite, la Kaolinite et la tuquoise. Sa proportion est de 1 :0.8 :0.6.

Keywords: excavations, clay minerals, dams, deformation, failures, weak rocks, weathering

The hydro-electrical power station in the upstream part of the Minjiang river in southwest China is the synthetic hydro-power plants combining the functions of irrigation, generating electricity, providing clean water, tourism and also it plays an important role in the control the water in the whole irrigation area. With a 156m high dam and a water level of 877 m under ordinary conditions, the total capacity of the reservoir is 1.112 billion m^3. The project area is located at a 180º river meander of the Minjiang River, which points in a NE direction, and all the hydraulic constructions are applied on the belt-like ridge on the right side and enclosed by the river meander, a "Ω"shape in plan. The inclination of the ridge averages about 20º ~25º and the NW side of the mountain ridge is relative steep in landform, at about 37º. The mountain on the left side of river is relative broad. Resulting from differential weathering on sandstone and shale, the landform is mainly stated as ridge and slot intersected with each other. The bedrock is quite obvious on the ridge. On another hand, the accumulation is well developed in the slot area.

The slope at the spillway in the construction area is identified as cross direction slope with different degrees argillized seams, which developed there. If argillized seams in slope have not been treated properly, under force of gravity and excavation, it could shear out along the strike direction, forming a weak rock foundation to provide space for potential further turn over deformation of the upper slope (Rong-Gui Deng et al. 2000), and at last formed compression-dipping and facturing deformation and failure patterns (Zhuo-Yuan Zhang et al. 1994).

STRATA AND ROCK CHARACTER

The outcrops in the construction area are mainly the second section of the Xujiahe Formation of Triassic age. The Xujiahe Formation is the main strata contained coal in the Sichuan basin, and the sedimentary facies are composed of continental and marsh facies intersected with each other and of Norian and Rhaetian age in the late Triassic. At Longmen mountain area, it is usually 300~500m thick on average. In Guanxian County, in the west part of the Sichuan basin, the strata of Norian and Rhaetian age are 4000 m thick with a depositional basin that stretched in a NE direction and it provided an ideal ancient geological environment for formation of original sheared rupture zone.

General speaking, the rupture zone is thick in the west and thin in the east in the construction area and in the lengthwise direction, the particle diameter of rocks largely follows the tendency of flysch-type from fine to coarse as carbonatite→sand-mudstone→conglomerate from west to east. The dimensional spread of sedimentary layers is made up of muddy shale in early period of the time, as well as topset beds consisting of mudstone or siltstone combined with coal with the property of deltaic deposits.

The strike of the second section of the Xujiahe Formation in the Engineering area is in a NE-SW direction. There are 15 cyclic strata consisting of grey or dark-grey, medium bedded sandstone with mid~fine quartz, sandstone with dolomite debris and calcium debris, as well as dark grey or black grey, medium or thin bedded siltstone, pelitic siltstone, carbonaceous shale with coal layers. There are sandstone layer with gravels at the base of each cyclic strata, and it gradually turns to fine sandstone, siltstone, carbonaceous shale and coal layer from bottom to top. It is flysch sediment and belongs to braided-like delta plain facies indicated by obvious cyclic strata and alternations from coarse to fine.

The strata in this area are influenced by the Shajinba syncline. The axis of the Shajinba syncline is N50°~60°E, plunging in a NE direction with a dip of 25°~35°. The NW limb of the syncline is more steep with an attitude of N25°E/SE∠60°~70° otherwise, the SE limb is relative gentle with an attitude of N45°~60°E/NW∠45°~60°. According to engineering investigation, the strata are quite complete; the boundary is very clear and evidence of compression and disturbance between each layer at the hinge point in the core of the syncline is quite obvious. This is caused by strong push and compression at the left bank of Minjiang river and the NE limb is reversed and SE limb is steep (60°~70°), and it forms a tight syncline, which is quite opposite from the syncline at the right river back.

PROPERTY OF CRUSHED COAL BELT

Based on the geological engineering investigation, the stability of engineering slope (Run-Qiu Huang et al. 1991) is largely controlled by the major fault of F_3 and F_{2-1} in the construction area. The F_3 fault is the largest weak layer in the engineering area compared crushed belt in each stratum. There are no big difference of rock mass properties between anti-shearing strength and anti-shearing index, and the mechanical characteristics of the rock are very poor as indicated by the loose structure and high compression deformation (Liang-Qin Tang et al. 2003).

The main composition of the layered rock mass in the engineering area is cyclic strata of sandstone with coal, siltstone and carbonaceous shale (carbonic shale), and with strong tectonic movement; the deformation is relatively dramatic. The crushed belt in different scale is widely spread at the construction site as trace of tectonic movement, and most of them come from the weak shale by shearing and disturbance during the process of folding. Characterized by large scale and long extension, except tangency in few areas, the attitude of the crushed belt is almost the same as attitude of the strata. Following to the sequence of the sediments, the crushed belts are numbered from L_1 to L_{15} from old to new. The L_8, L_9, L_{10}, L_{11}, L_{12}, L_{13} and L_{14} which are controlled by the Shajinba syncline, are closely related to stability of the excavated engineering slope (Table 1).

Table 1. Distribution characteristics of the main coaliferous interbedded shearing fracture zones in the engineering area

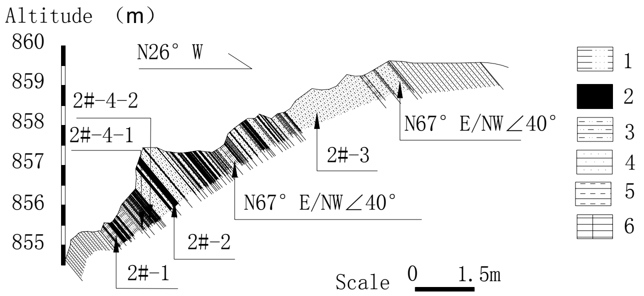
No.	Attitude	Thickness of crushed belt	Main property of crushed belt	Status of crushed belt
$F_{2\text{-}1}$	N79°W/NE ∠40~55°	*6~8 m*	The main composition is mylonite, breccia, and crushed sandstone. The attitude of strata in hanging side (left bank) and heading side (right bank) are quite distinguished from one another by means of intersecting at large angle, and in detail, attitude of heading side is in normal condition, otherwise, it has been reversed at hanging layer.	It is located at the corner of the meander. From Zhuluoba in SW at left river bank, it spreads in the direction nearly EW direction, and turns to the SEE gradually after crossing the Minjiang river. It has crossed the Minjiang river again after passed the flood plain at right river bank, and turns to a NE direction into Maliu gulch. In upstream of toe board line, it followed river and Maliu gulch.
F_3	N50~70°E/ NW∠50°~ 75°	55~87 m	The main composition is carbonaceous shale and coal layer. Because of strong corrugation, mylonite spread in schistose layer by means of massive lens-like as main part of fault. The fault clay is 20~100 mm thick on average characterized by plastic and slip in bedding surface and secondary surface, some particularly fault clay is 500 mm thick. Also, there are breccia and lens-like sandstones widely spread in carbonaceous shale, and rock in fault is easy to slake at fast speed when in contact with water.	It is located at 360 m downstream of dam axis, the erosion section of outlet of spillway, flood tunnel, and sand sluicing tunnel.
L_{14}	Same to strata	2~10 m	Rich in coal layer, carbonaceous shale, debris and mylonitic after compression and shearing	Core of syncline at river bed $T_{3\ xj}^{3\ \ 14\text{-}⑤}$
L_{13}	Same to strata	2~10 m	Rich in coal layer, carbonaceous shale, debris and mylonitic after compression and shearing	Foundation and toe of dam $T_{3\ xj}^{3\ \ 14\text{-}②}$
L_{12}	Same to strata	6~12 m	Carbonaceous shale with thin layered siltstone, mess of bedding and with disturbed surface	Intake tunnel at right river bank $T_{3\ xj}^{3\ \ 13\text{-}⑨}$
L_{11}	Same to strata	8~38 m	Carbonaceous shale and coal layer with lamellar loose muddy siltstone	Intake tunnel and sand sluicing tunnel at right river bank
L_{10}	Same to strata	2~5 m	Loose and fractured carbonaceous shale, muddy shale	$T_{3\ xj}^{3\ \ 13\text{-}③}$
L_9	Same to strata	6~13 m	Carbonaceous shale in upper layer, muddy shale with lamellar mudstone in lower layer	Sand sluicing tunnel, spillway and factory building at right of river bank $T_{3\ xj}^{3\ \ 12\text{-}④}$
L_8	Same to strata	6~7 m	Loose and fracture Carbonaceous shale with disordered bedding	Outlet of flood tunnel $T_{3\ xj}^{3\ \ 9}$

The weak crushed layer is largely developed between the hard sandstone and carbonaceous shale or mud-shale, or between Carbonaceous shale and coal layer, and the structural traces, such as crushed calcite scratch and step, can be read on the bedding of the sandstone. It is well developed in weak layer such as coal layer and mudstone, flexions as well as secondary folds. The degree of plastic deformation is much greater than in the stiff sandstone layer, and it also provides more space for deformation of overlying strata (Qi-Hua Zhao et al. 2001).

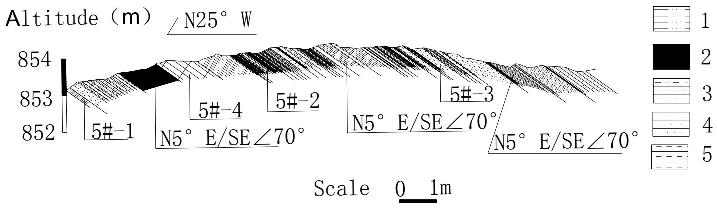
DISTRIBUTION PROPERTY OF ARGILLIZED SEAMS

The weak layers developed along the engineering slope and belts spread in dimension. Caused by tectonic compressing movement, it has formed sheared, interbedded crushed belts (Gao Liu & De-Xin Nie 2000). According to anticipation of measured profile in the field, the proportion of soft rock and hard rock is 30%:70%. Meanwhile, the four main petrofabrics are argillized seams, coal, carbonaceous shale, and mud-siltstone and can be distinguished in the field.

Argillized seams come from several periods of compression and crushing during tectonic movement of the original rock, and the rock property can be attributed to carbon-debris muddy shale, muddy siltstone, fine-psephite-mudstone, or any combination. In general, the rock character is very complex, and it highly related to the original rock. The argillized seams developed on the inner side slope of the spillway is very typical (Figure 1.II-II′ and V-V′ profile). The proportion of different petrofabrics in profile is indicated in Table 2.



II-II′ Section of formation(L_9) in 1# drain outlets of inner side slope at lower part of spillway



V-V′ Section of formation(L_{12}) of outer side slope in upper spillway

Figure 1. Sketch of distribution of formation in one of typical sections
1 carbonaceous shale 2 coal 3 mud-siltstone 4 mid-fine sandstone 5 argillized seams 6•mud-shale

Table 2. Ratio of Ingredient in formation in soft belts of the engineering area

Petrofabric	Measured profile in the field			
	II–II′ (L_9)	V–V′(L_{12})	VI–VI′(L_{10})	Inner side slope of spillway(L_{11})
Argillized seams	2.7% (2#-4-1, 2#-4-1)	1.77% (5#-4)	27.21% (6#-4)	6.09%
Coal layer	10.87% (2#-2)	7.13% (5#-2)	4.08% (6#-2)	16.90%
Carbonaceous shale	17.60% (2#-1)	41.44% (5#-1)	27.30% (6#-1)	22.79%
Mud-siltstone	68.83% (2#-3)	49.66% (5#-3)	41.41% (6#-3)	54.22%
proportion	1:4:6.5:25.5	1:4:23.4:28.1	6.7:1:6.7:10.1	1:2.8:3.7:8.9

THE FORMATION MECHANISM OF ARGILLIZED SEAMS PETROFABRIC

According to the geological identification of coal, carbonaceous shale, and mud-siltstone in coal series formation (mainly concerned with sheared, interbedded crushed layers), the existence of clay minerals such as illite, kaolinite, and chlorite have not been found there and there is also no kaolinite in mid-fine sandstone and debris sandstone. It is suggested that the feldspar of this petrofabric has not been influenced by acid water. Meanwhile, combining all the factors in synthesis of the geological information in this region and measurement of profiles in the field, the several main stages of the formation mechanism of argillized seams is indicated as follows after systematic analysis:

1) Original bedded formation of upper Triassic, which also named coal layer, is formed in a relatively stable limnetic lake and marsh facies environment.

2) Under several strong compressions caused by tectonic movement, the soft rocks such as carbonaceous shale, mud-siltstone, and coal were compressed and crushed, and they also formed uncemented debris and powder cut by several structure planes.

3) With changes of environment, the leading effect applied on crushed rock is physical weathering: first, the integrity of the rock has been destroyed, and then after later transformation of tectonic movement, it continues slaking to form debris or grains with different sizes. After experiencing the processes above, it forms interbeded shearing crushed layers. However, it also be called original mineral because it has the same ingredients as the original rock.

4) With further developing of other kinds of weathering, especially the penetration of surface water or underground water, chemical weathering plays a more and more important part in the whole weathering process. Not only did grains become finer, but also some changes happened in the chemical ingredient. Part of new mineral, known as secondary clay minerals (De-Fang. Kong 1991), such as illite, kaolinite and chlorite, have been formed by the process of displacement.

The grains of clay mineral surface are usually presenting negative electricity because of displacement of isomorph and dissociation. With a negative electric field around the particles, the positive electricity will be absorbed to balance the negative electric field, and then, the electric double layers are formed around the particles (Xian-Gong Zhang &

De-Xin Nie 1990). The results of X-ray diffraction tests are indicated at Figure 2 and Table 3. Meanwhile, it is identified that there are also new clay minerals in the argillized seams.

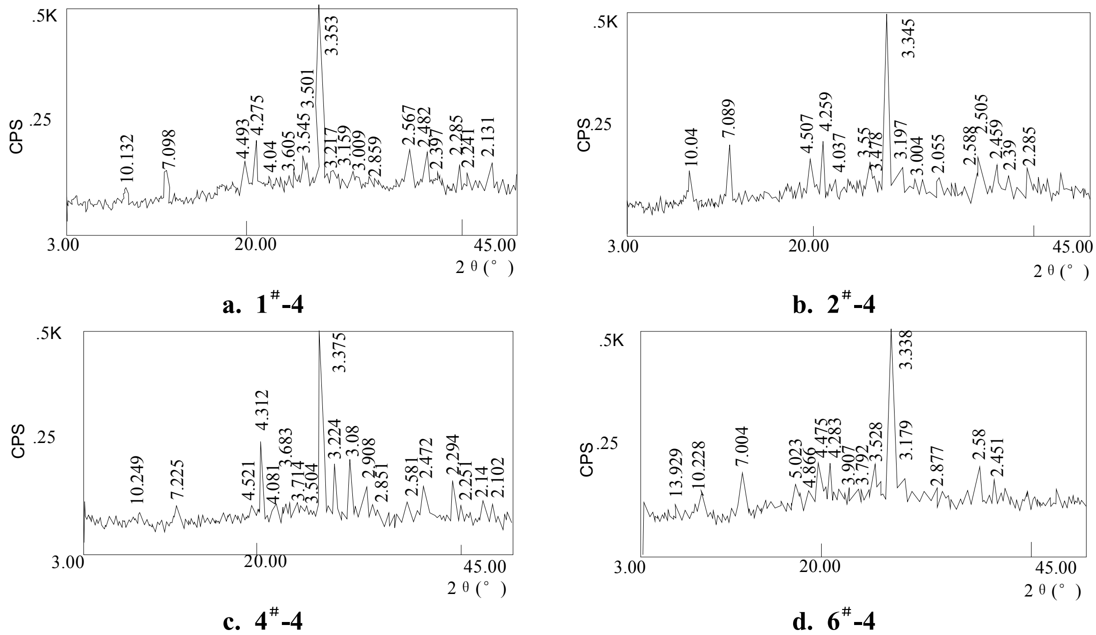


Figure 2. X-ray analysis curves of argillized seams

Table 3. Test results of X-ray analysis of argillized seams

Sample No.	Test result (%)							illite: kaoliniate: chlorite	Test condtion
	Secondary clay minerals			Original clay minerals					
	illite	kaoliniate	chlorite	quartz	feldspar	calcite	dolomite		
1#-4	23	12	22	40	3	/	/	1:0.5:1	D/MAXIIIC diffractometer, CuKa,
2#-4	32	14	19	26	5	3	/	1:0.4:0.6	Ni filtering, 35KV,
4#-4	10	22	/	46	8	9	5	1:2.2:0	
6#-4	45	/	32	17	3	/	3	1:0:0.7	25mA, 6°/min.

(Test by College of Materials and Bioengineering, CDUT)

5) The electric double layer will be varied, on condition that the mediators around them have been changed. The results of ion exchange could possible change the thickness of electric double layer. At the same time, a large proportion of fine grains will be produced in the crushed belts caused by tectonic movement. The large area surface resulting from finer particles implied the thickness of electric double layer will be thicker. Also, with change of mediator, the particle has experienced the process of conglomeration and decentralization several times, which is crucial to engineering geological properties of argillized seams.

The composition of clay minerals plays a very important role in the engineering geology of argillized seams, because it will control engineering geological properties even if it is not in dominant proportion, particularly the hydrophilic clay mineral. It is potential stability incipient of rock slope, and under a certain circumstance, even causes failure of slope.

CONCLUSIONS

After describing all the properties of argillized seams, a few conclusions can be drawn and specified below:

(1) Influenced by the original geological environment, the strata in engineering area are flysch-style sediments. The shearing crushed belt with coal layer caused by compressional tectonic movement is mainly controlled by the Shajinba syncline in dimension.

(2) After measuring and calculation of strata profile, especially some weak belts such as L_8, L_9, L_{10}, L_{11} and $L_{12,}$ the proportion of soft rocks to hard rocks is 30%:70% in the entire construction area. Meanwhile, at least four types of petrofabrics can be classified as: argillized seams, coal layer, carbonaceous shale and pelitic siltstone. Based on some typical measured profiles, it can be found that the proportion of argillized seams, coal layer, carbonaceous shale, and pelitic siltstone is 7.2%:8.6%:30.2%:54.0% or 1:1.2:4.2:7.5.

(3) The rock characteristics of agillized seams are very complex and five different stages to describe the evolution of them have been presented. After X-ray diffraction tests on minerals in the argillized seams, the secondary clay minerals such as illite (the most), kaolinite, and chlorite can be identified and the proportion of them is 1:0.8:0.6. It is potential stability incipient of rock slope, and under a certain geological environment, even causes failure of the slope,

because bedding plane of weak layer will provide room for rock mass above to shear out, or offer more space for displacement and form compression-dipping and fracturing failure. Moreover, it could deteriorate the integrity failure process of the slope.

Acknowledgements: This Project is financed by the Fund of the National Laboratory of Geohazard Prevention and Geoenvironment Protection of Chengdu University of Technology.

Corresponding author: Cao Yun-Jiang, Chengdu University of Technology, No.1, Erxianqiao Dongsan Road, Chenghua District, Chengdu, Sichuan, 610059, China. E-mail:caoyj-xt@sohu.com, Tel.: +8613183801427(M), Tel.:+86-0732-8290610(H)

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