Stability analysis and safety assessment of high cut slopes in new towns for the Three Gorges Project population migration, China

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Abstract: The TGPC (Three Gorges Project of China) involves large scale migration along the banks of the reservoir. In order to ensure that the project keeps on track, the inhabitants in the reservoir area will be moved to tens of new towns to be built according to a planned schedule. This work has been going on for almost ten yeas. So far, most new towns have been completed and some of them have existed for quite a long time. Because these towns have grown in a very short time and brought about a remarkable impact to the geoenvironment, some hidden geohazard problems have resulted. Therefore, it is necessary to have a systematic check of the geotechnical issues of the new towns after a period of existence. Considering the common concern about cut slopes, the authors have looked at the stability of cut slopes and the safety of retaining structures to conduct a feed-back investigation and assessment selecting Fengjie as a typical example. Firstly, we suggested a working framework including the essential data collection and technical analysis for safety assessment of cut slopes The following aspects were considered:- basic geological conditions, harmony of interaction between buildings on cut slopes and geological conditions, status of retaining works and the geotechnical investigation, and design and construction of the slopes. All these aspects were further divided into a series of specific items and indices. Then, a step by step checking procedure was put forward and a safety grade classification for cut slopes and retaining works was established according to the favourable and unfavourable evidence obtained from in-situ observations. The main factors affecting stability of cut slopes and safety of retaining works were analyzed. The stability and safety status of all 152 cut slopes in new Fengjie town were evaluated using this framework. Some potential unstable slopes were discovered and their future stability was predicted. Finally, some measures for geohazard prevention of these slopes were suggested.

Résumé: La nouvelle stabilité géologique suscitant par le changement de la géologie et de l'environnement causé des travaux de l'implantation de déplacement de la région du réservoir de trois gorges. Il est déjà influencé et influencera le fonctionnement du réservoir et la retenue d'eau normale de la deuxième et troisième périodes. Le texte raconte le sens, la constitution et la ligne technique de séance de travail de l'évaluation de la sécurité du haut perré de la région du réservoir à travers de l'évaluation de la sécurité du haut perré de la nouvelle ville du District Fonjié. On a analysé la cause principale influençant la stabilité du haut perré et la sécurité du soutènement des ouvrages sur la base de la recherche et des données techniques au cours de la construction. Par le contrôle du haut perré de 152, l'évaluation de la situation et l'évaluation prévionnelle, on a synthétisé le résultat de l'évaluation de sécurité. En même temps, on a proposé le traitement du haut perré de l'instabilité et de moins stabilité et le problème attentif de la construction à l'avenir de la région du réservoir.

Keywords: Slope stability, case studies, geological hazards, dams, environmental impact, risk assessment

INTRODUCTION

Many towns in Three Gorges have a long history of several hundred and even thousand years. Natural geohazards were not a problem in these towns. The towns were built according to the physiognomy of the hills nearby, and a harmonious environment between human and nature was formed. New towns in the reservoir area of Three Gorges with a complicated landform were built to the standards of modern towns for the last ten years. During their construction landforms and geological environments were changed. Hence the geohazard risk induced by growth of new towns may be greater than that of any period in the history. According to the regional geological survey in 2002 there were 7000 places where landslides had occurred, 2500 places with water flow, and about 90 gullies of debris flows in 20 counties of Three Gorges reservoir area. At present national monitoring engineering for momentous landslips and landslides has been implemented, with 250 points of regional monitoring, 1000 points of countryside monitoring and 4000 points of village monitoring. In 2003 185 secondary projects for landslide treatment, 22 excavations, 74 reservoir bank protection and 1490 high cut slopes were finished. Tertiary mitigation projects included 418 landslide treatments, 399 movement of people, 35 reservoir bank protection and 1270 high cut slopes.

After a new town is built monitoring is usually required for a period of time. The towns built quickly in the Three Gorges Reservoir area needed a longer time for monitoring. Although not all the latent geological issues caused by the engineering were expected to be completely exposed it is obligatory for predicting occurrence of sudden geological events through observation and analyzing new geological and environmental issues happening in the towns during the monitoring period.

During the monitoring deformation of foundations or artificial slopes may occur. The geological reason causing this kind of deformation is geology defects of the foundations or the slopes. This kind of problem needs investigating and surveying during the monitoring period in order that similar hazards can be prevented from occurring to minimise damage to new towns. Therefore in order to ensure safe operation of new towns it was necessary and quite important to fully appraise the safety of the new towns.

Based on the evaluation of Fengjie new town this paper introduces the stability evaluation of the high cut slopes, their safety evaluation, programme of works, operation mode and progress, and evaluation results. Meanwhile, this paper analyzes the cut slope stability and the factors affecting sustaining-the retaining structure security and proposes treatment measures.

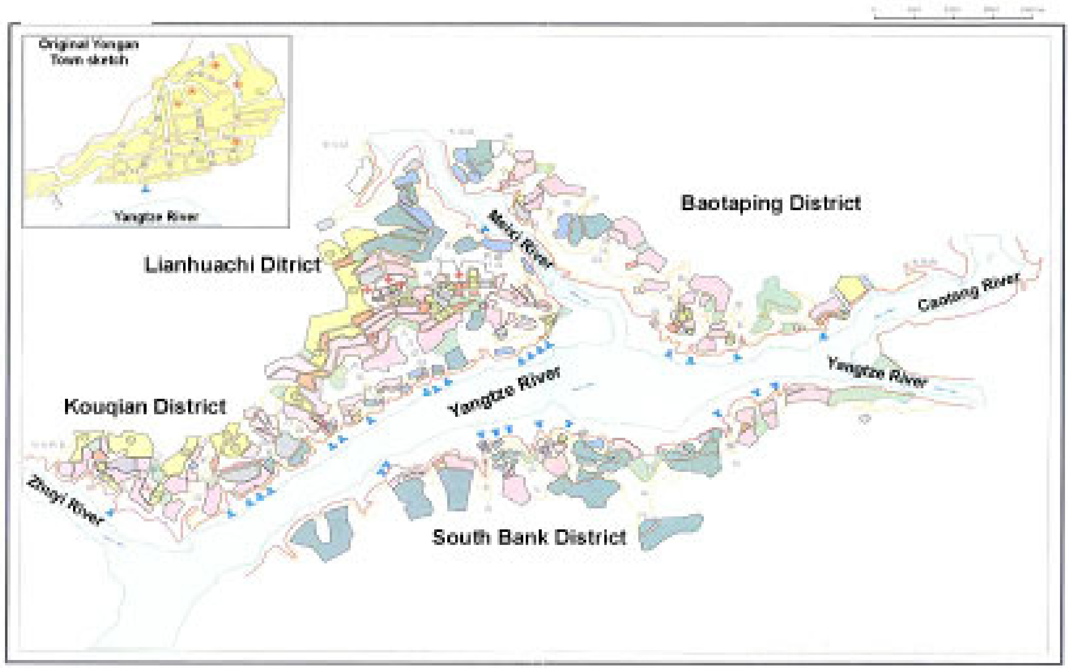

Figure 1. Fengjie County planning (After Urban Planning Institute in Sichuan)

IMMIGRATION SUMMARY OF FENGJIE NEW TOWNS

According to *notice of building land scale for town immigration in Chongqing reservoir area of Three Gorges* from Chongqing Immigration Office, 6.3588 km^2 land for immigration buildings was approved in Fengjie County. In the course of the county construction Fengjie County Government considered some building lands needed adjustment, and then declared *the requisition of partial adjustment of immigration planning for the new towns in Fengjie County*. In the reply from Chongqing Government 0.618 km^2 land of Wangjiaping, Kouqian District was adjusted for immigration building lands; in former Kouqian District immigration and building land of 1.5008 km^2 was changed into 2.1188 km^2; in Lianhuachi District immigration and building land of 1.4149 km^2 was reduced to 0.7969km^2. After the modification the total immigration and building land of the County covered 6.3588 km^2. Until now actual land area for immigration and building is 6.84 km^2.

The new towns started to be built in late 1996. Until 2003 the city zone had been formed with 1.49 million km^2 buildings, 74 km roads and 13 bridges. Population in the city zone is about 80000 to 100000. Construction of new towns has converted the original sloping landforms into multilevel sidesteps such as the four-stage sidesteps of Wangjiaping (Figure 2 Caiyun Street, Yusheng Street, Zhuzhi Street and Scicheng West Road), ten-stages at Liujiabao, six-stages at the back of Sanmashan and four-stages at Sanmashan. The height of high cut slopes between every two sidesteps is usually between 10 m to 100 m. Therefore the county comprises stepladder-like construction groups with super-high artificial cut slopes with the slope heights of more than 20 m.

Therefore the long-term stability of the County depends on the stability of high or super-high artificial cut slopes between the construction groups. Evaluation of the artificial high cut slope stabilization was a major part of the safety evaluation of the County with a core activity being an assessment of the geological conditions.

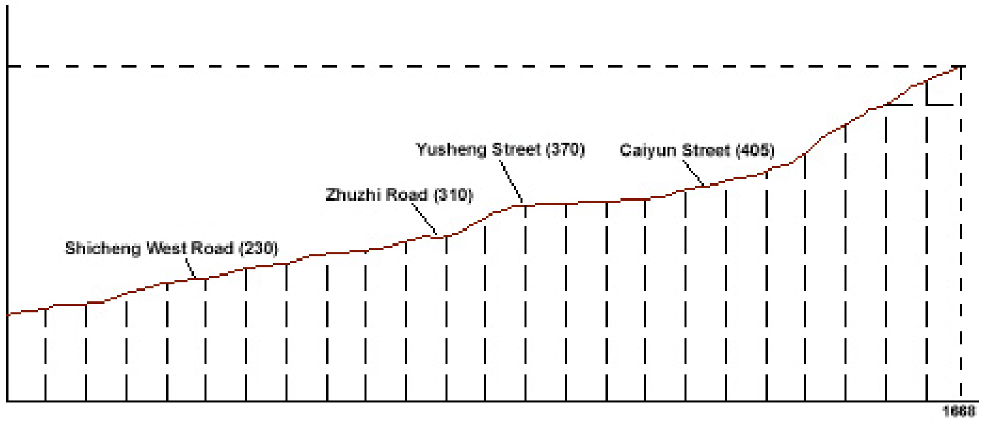

Figure 2. Land form profile of Wangjiaping District

APPRAISAL CONTENT AND TECHNICAL ROUTE OF HIGH CUT SLOPE

Appraisal content of high cut slope

The procedure described in this paper to evaluate the safety of slopes can be followed in Figure. 3. According to empirical rules, standards and local criteria the procedure was as follows:-

1) Assessment of the natural stability;
2) Harmony between the foundation, the geological conditions and the construction are gained through on-the-spot observation, referring to and checking the construction of the foundation, the geological baseline, the design, the construction, the supervision, and the contract documents;
3) Recording the as constructed structures and monitoring until now;
4) And generating general appraisal results according to the evaluation ranks criteria.

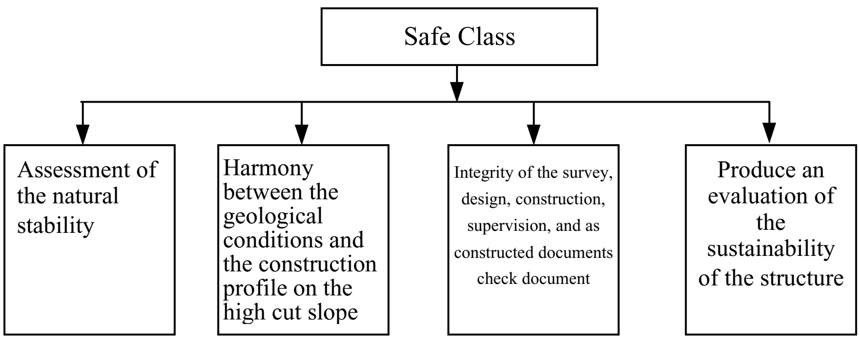

Figure 3. Safety appraisal procedure for high cut slopes in the County

Technical appraisal

The technical evaluation can be seen in Figure 4.

Ranking the stability of high cut slopes

The stability state of high cut slopes can be divided into four categories.

1) Stable slopes

i) The slope is wholly stable; ii) there is not much deformation evidence such as unloading cracks parallel to the slope surface, or differential settlement at the top of the slope; iii) there is no new deformation evidence such as bulging, shear slide and settlement below the middle part of the slope, especially at the toe of the slope; iv) no deformation evidence of the structural reinforcement of the slope; v) no groundwater activity at the slope surface and toe; and vi) a perfect drainage system.

2) Basically stable

i) The slope is wholly stable; ii) on the whole it conforms to No. (i) and (ii) in Category 1; iii) local deformation is evident at supporting structural units; iv) water is observed at fractures; v) the drainage system requires improvement.

3) Lack of stabilization

i) The slope is basically stable; ii) there is deformation evident such as unloading cracks parallel to the surface of the slope, differential settlement near the top of the slope; iii) new, local deformation evidence such as bulging, shear slide and settlement; iv) deformation evidence of structural reinforcement such as anchors; v) water seeping from the slope; vi) incomplete drainage system.

3) Unstable

i) The whole slope is unstable; ii) there is evidence of deformation such as unloading cracks parallel to slope surface, and differential settlement; iii) there are signs of bulging, shear slides and settlement below the middle part of the slope or at the toe; iv) supporting units reinforcing the slope with anchors and cable-anchors are damaged; v) groundwater can be seen to seep from the slope surface and the toe; vi) and there is no drainage system.

Safe class of sustaining-retaining structure

1) Safety situations

i) Coordination between the geological conditions and the foundations accords with safety standards; ii) there is no evidence that foundations and structures are deforming; iii) perfect drainage systems; and iv) there is no unusual groundwater flow.

2) Basic safety situations

i) Basic coordination between the geological conditions and the foundations accords with safety standards; ii) there is no evidence that foundations and structures are deforming, but local deformation can be occurring; iii) drainage systems need improvement; and iv) there are unusual groundwater flows.

3) Lack of safety and requirement of monitoring

i) Lack of coordination between the geological conditions and the foundations and bases; ii) deformation evidence of the foundations and the structures; iii) incomplete drainage; and iv) groundwater flow evident.

4) Unstable situations

i) Separation of foundations from the underlying geology; ii) the foundation and the structure show greater evidence of deformation and even failure; and iii) there is no drainage.

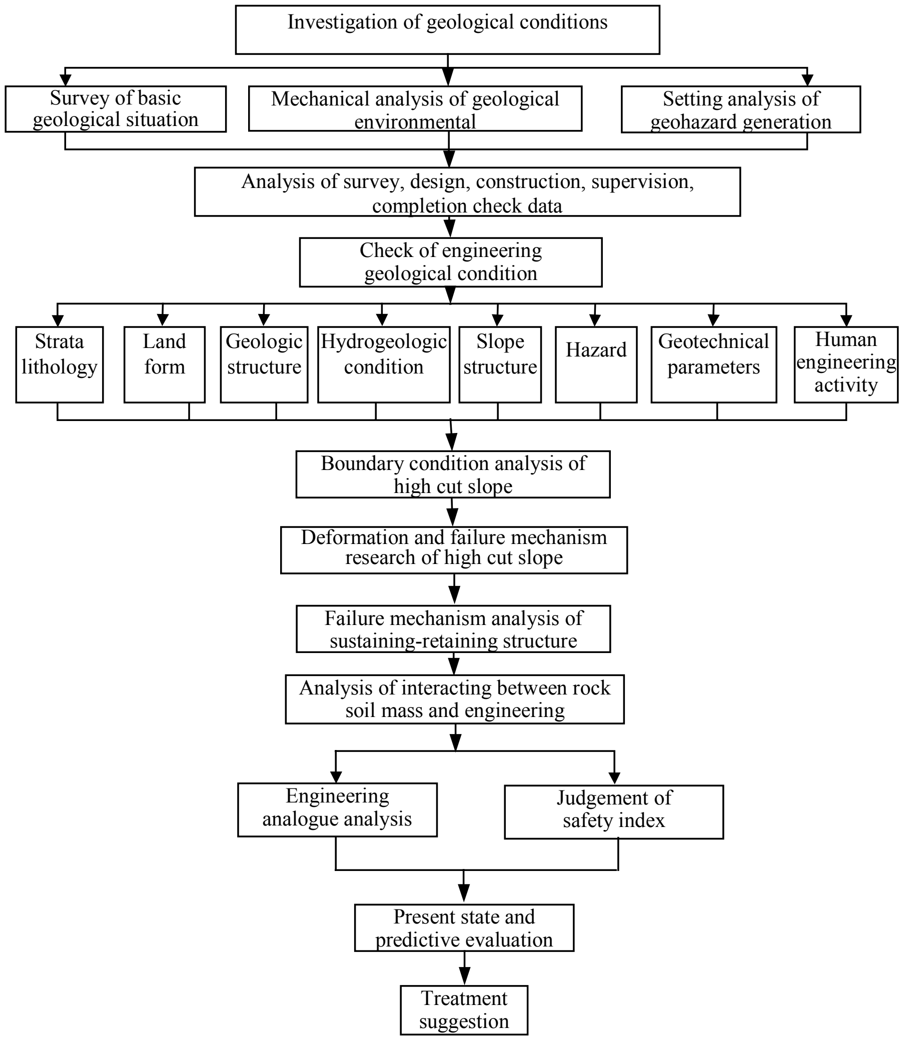

Figure 4. Technical route of appraisal work

ANALYSIS OF THE FACTORS AFFECTING STABILITY OF HIGH CUT SLOPE AND SAFETY OF SUSTAINING-RETAINING STRUCTURE

Landform

Fengjie new towns are located in low lying hills of the eastern Sichuan. The peak altitude varies from 1050 meters to 1350 meters, and the site from 182 meters to 450 meters. The Yangtze River runs through the region with a NE 35^{0} trend, and turns at the estuary of Meixi River, and finally flows into Jutang Gorge. Zhuyi River and Meixi River, two branches of the Yangtze River, develop along the 16 km reservoir bank lines along its north side. The new city zone in Fengjie County is situated along the banks of the main river and its branches on the two sides of the Yangtze River, and goes through the areas of Kouqian, Shujiagou from the Zhuyi River, old County, Wulibei on the right side of Meixi River, Pianyazi on the left side, and Jinpan and Baotanping from the upstream to downstream.

Due to the difference in the strength of the slopes of the south bank of the Yangtze River, which comprise clay soil, argillaceous siltstone from second segment of Badong Group (T_2b^2), the slopes have an average inclination of 16^o to 20^o; the slopes in the north are composed of argillaceous limestone from third segment of Badong Group (T_2b^3), and the average inclination is 21^o to 25^o. Therefore there is an unsymmetrical U-shape valley with gentle slopes in the south and steep landforms to the north. Forty two gullies have developed in the New Town which include 13 grand-scale gullies, 11 large-sized ones and 9 middle and small-sized ones. Lida gully, Baiyangping gully, Sunjia gully, Dahe gully, Dayingpan gully, Laolongdong gully, Shiban gully of Jinpan, Chenjia gully of Baotaping, Wanjia gully, and Yangcha gully are related to the project as they are adjacent to the reservoir.

During the construction of new towns original landforms were artificially reshaped. Hills were levelled and valleys filled in order to accommodate 0.13 million people. Therefore high cut slopes and structures on cut and fill are common.

Fengjie new town is built in an area of low hills. During the construction programme excavation and fill of stable slopes led to a large number of high steep slopes. This altered the natural stability of existing slopes. Reinforcement has been widely used to stabilise high steep cut slopes. Therefore these slopes area a threat to the new town.

Strata and lithologic associations

Exposed strata in the region investigated included Xujiahe Group of the Upper Triassic, Badong Group of the Middle Triassic, Jialingjia Group of the Lower Triassic, a residual horizon, landslide and rockfall deposition, and alluvial deposits. The main lithologic characteristics are:

1. Alluvial-proluvial horizon (Qal+pl): Silt, fine sand, gravel and pebbles at the riverbed of the Yangtze River and the branches; Silty clay at the upper part of the benches, gravel and pebbles at the lower part of the benches, float stones, block stones and pebbles at the base of the gullies with a maximum thickness of 30 meters.
2. Residual horizon (Qdl+el): Gravelly clay, and debris soil aggregated with crushed block stone with a thickness commonly from 1 to 4 meters with maximum thickness of 20 meters.
3. Rockfall deposit horizon (Qcol+el): Rock block, gravel containing debris soil aggregate witha thickness of 5 to 10 meters.
4. Landslide deposit horizon (Qdel): Slipping rock mass and debris soil aggregate from the rockbed, and block stone and gravel containing debris clay with a thickness from 0 to 40 meters.

According to the statistical data most landslides in the reservoir area developed in mudstone, marlite and argillaceous limestone from second and third segments of the Badong Group of the Middle Triassic. The talus slides slipped along the original rock surface, which are composed of soft slope washes and weathered residual unconsolidated debris. The kind of slide belongs to a deep landslide due to its great thickness. Superficial slope destabilization in Fengjie County has marked characteristics, which is the conclusion of many geological engineering specialists and scholars. The description of superficial slides used before has been reviewed and redefined. There is no sliding surface between the debris and the rockbed, which are both cracked rock mass and present transitional connections. Large-volume debris is distributed at the T_2b stratum adjacent to the top of the slope. There are no large-volume unstable rock bodies at the back of the debris.

Change of surface water, groundwater and reservoir water level

Recharge and charge of surface water and groundwater

Water is one of the important factors for the destabilisation of slopes leading to long term stability problems for retaining structures in Fengjie County. This is due to:-

1) Construction of buildings, roads, docks and squares reshapes the ground surface, and alters the natural drainage system resulting in a change in the saturation line;
2) Levelling of the ground and constructing the roads bares the surface of the slopes, which increases the infiltration of atmospheric water. Therefore the rock and soil bodies can become saturated and their mechanical strength is reduced.
3) Gullies formed by original landforms were the main pathways for ground water drainage. However, artificial backfill and waste residues in the gullies hinder the drainage, which results in surface water infiltration into the slope bodies. As a result hydrodynamic pressure in the slope bodies is increased and the slope stabilization conditions are worsened.
4) And there are no perfect subsurface sewage discharge systems. Lack of adequate design, planning and quality construction has resulted in sewage infiltrating into the rock and soil mass of retaining walls increasing the water content of the Quaternary strata. This is a key factor inducing slope failure and retaining wall failure.

Charge and discharge problems of surface water and groundwater are as follows:

1) No drainage and protection measures for the slopes;
2) Protection and the design of surface water and groundwater systems are unreasonable or they have been destroyed;
3) And foundation backfill and waste residues hinder the discharge of superficial water.

Reservoir filling and water level fluctuation

Reservoir banks in Fengjie New Town (from Lijiada gully to Longdong gully) were divided into 12 segments. Reservoir bank segments could be separated into rockbed bank slope, rockfall debris slopes, and thin and thick residual slopes. The total length of rock banks is 2142 meters, which occupies 20.7% of the total length; other banks occupy a total length of 8210 meters (79.3% of the length of slopes to be assessed). In each segment there are many geohazards. For example, during the investigations survey teams considered landslides such as the Laofangzi, Sichouchang, and Houzishi landslides and a deformed body such as the Dahe gully. These latent ancient slides and deformable bodies were partly or fully below the impounded level of 175 meters. Due to 30 meters fluctuation of water level caused by adjustment of the reservoir level in the Three Gorges Reservoir, unstable loose bank slopes, and alteration of the ground water level zone which varies from 145 to 175 meters in altitude, means that water will flow in and out of the slopes. Besides, these ectodynamorphic factors reducing the bank slope stability there are also issues related to water-rock interaction, hydrostatic and hydrodynamic pressure actions, storm waves, waves created by boats and erosion due to flow. It is quite likely that new slides will be created and old slides will be reactivated as the reservoir level changes. Therefore the communication network created by the rivers is directly or indirectly threatened.

The effects of reservoir water height on the slope stability are presented as follows:

1) Long-term soaking action of reservoir water. This kind of action reduces the strength of the soil. As the strength of the rock or soil gradually decreases to an equilibrium level collapses can occur in the bank with possible slide, and even slides happening.
2) Erosion action of reservoir water waves. Erosion of the banks can lead to loss of superficial soil and infill soil from intensively weathered zones in rock slopes.
3) Effect of reservoir water height fluctuation on hydrogeology parameters. Rise and fall of the reservoir water height alters the hydro geological conditions of rock and soil bodies, resulting in changes in the hydrostatic level and dynamic water level in the bank. This has a greater effect on slopes comprised of soils with low permeability. Slopes can fail.
4) Combined action of surface water and groundwater. During heavy rainfalls surface water from valley sides and groundwater makes the soil mass saturated increasing its self-weight. This can cause local instability and major slope failure.

The paper investigates two conditions: - normal reservoir level of 175 meters and dead water level of 145 meters from Lijiada gully to Laolongdong gully. It is probable that the Laofangzi landslide between the Chenjia gully and the Sunjia gully, the Houzishi landslide between the Baiyangping and Shuijing gullies, the deformation body of the Dahe gully, and the residual bodies of the Baijiayangping-Chenjia gullies may be reactivated. Therefore they have to be investigated.

For example, under natural conditions the Houzishi landslide is basically stable; as the reservoir water level begins to rise and submerge the landslide its stability factor gradually decreases. When the reservoir water level arrives at normal reservoir level of 175 meters its stabilizing factor ranges from 1.01 to 1.03 and the slope approaches limiting equilibrium. The stability factor is only 0.94 to 0.99 when the reservoir water level rapidly falls to 145 meters from the upper water level of 175 meters. If heavy rainfall and an earthquake are considered then its stabilizing factor is from 0.89 to 0.92. Consequently it can be seen that the reservoir banks need to be checked.

Engineering structure factor

Additional load of the structure at the top of retaining wall

Building loads alter the earth pressure in the slopes and frequent vibrating loads from traffic affect the slope stability. Apparently additional loads at the top of the retaining walls were not included in many slope designs of Fengjie County. At the same time the embedded depth of some building foundations were higher than that of retaining walls, which meant the building foundations failed to lie in stable horizons.

Rigid connections between the structures at the slope toe and slope retaining walls

In the investigation it was found that there were rigid couplings using reinforced concrete between many construction walls and slopes or retaining walls. For example, the house below the road from Kuizhou Hospital Building to the Pedestrian Mall, and the building below Wujiawan Road were danger. Deformation of the buildings and slopes should be monitored; control measures such as cutting off the beams of reinforced concrete and use of anti-slide piles should be taken to control lateral deformation of the slopes or the retaining walls.

SAFETY APPRAISAL RESULTS

The Evaluation Team undertook in situ investigation and data collection for 152 high cut slopes for 40 days and analysis and collation of the data for a further 30 days. There were 10 rock slopes, 19 rock and soil slopes and 123 earth slopes investigated. 148 of all the high cut slopes had been treated, and included 95 gravity retaining walls, 3 anti-slide piles, 3 pile sheet retaining walls, 33 ribbed plates, lattices and anchors, and 14 multiple retaining walls. In the appraisal report there were 16 slopes that were considered unsafe and 6 slopes that were at the point of failure. Different grade distributions can be seen in Figure 5.

CONCLUSION

1) An evaluation of the stability of 152 high cut slopes related to immigration in Fengjie County led to three categories of slopes according to slope type, height and failure mechanisms. 130 (85%) slopes were found to be safe, 16 (11%) slopes were found to be just safe and 6 (4%) slopes to be unsafe. Most slope treatment measures for high cut slopes were found to be reliable. Stabilisation of the high cut slope contributed to the fact that the new towns could be built and the reservoir filled on time.
2) Main geological issues induced by engineering construction or failure included inadequate drainage systems for the slopes or the retaining walls, incomplete rain and flood hazard prevention and mitigation systems, and not assessing the affect of building on retaining walls and cut slopes. Engineering construction and monitoring needs to be coordinated.

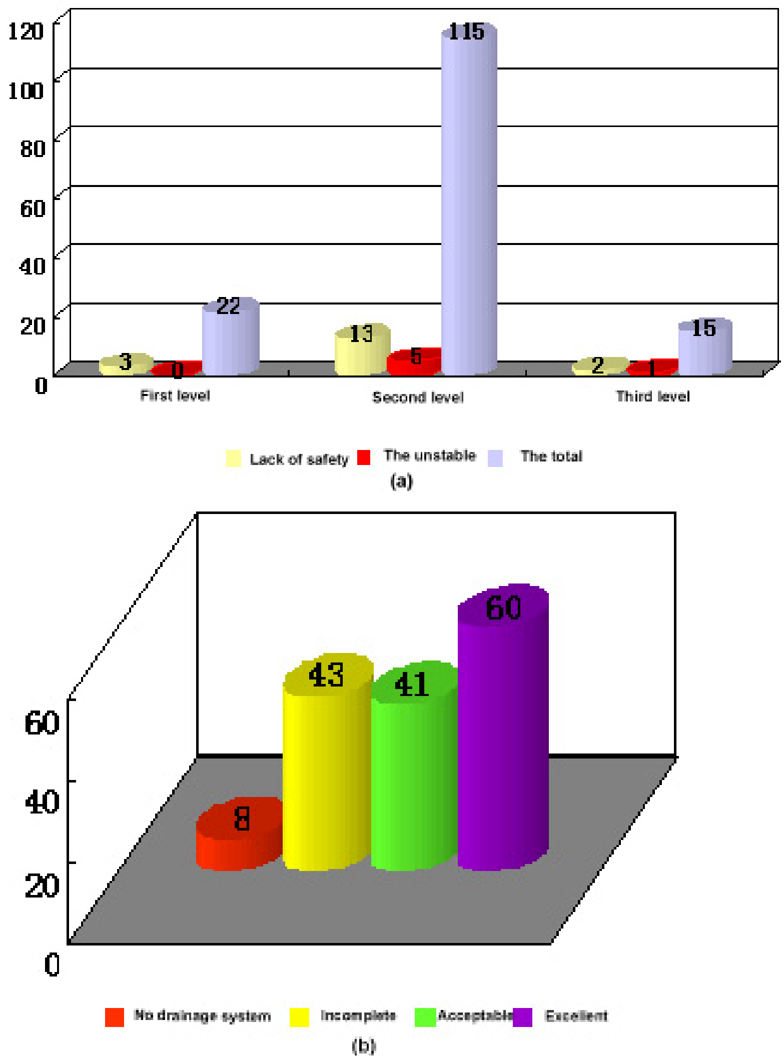

Figure 5. Safety appraisal results of high cut slopes in Fengjie New Towns: (a) appraisal results of different safety grades for high cut slopes; (b) investigation results of drainage systems of slope engineering

Following this appraisal the following recommendations for preventing failure of high cut slopes are as follows:-

1) Perfection and maintenance of drainage systems including the surface water drainage systems, the sub surface drainage systems and the city sewage systems.
2) Complete slope monitoring system should exert an influence on treatment of the slopes.
3) Further checking of the stability of the slope with different scenarios to take into account changes in plans should result in guidelines for additional stability mitigation measures.
4) Rock retaining walls, rockfall trenches and protection nets used where necessary.
5) Vegetation protection measures reinforcing the slopes should be taken.

The problems should be noticed in new construction as follows:

1) In principle excavations and construction should not be permitted at the toe of the slope. If the toe of the slope has to be excavated then feasible measures must be used to prevent failure. If new structures are to be built at the toe of the slope then their foundations should be kept some distance from the slope to avoid adverse influence on the slope stability; or else mitigating measures are necessary.
2) Changes in the groundwater regime should be considered.
3) All construction land use should be strictly examined and approved.
4) A geological risk assessment of construction land should be carried out.
5) The disposal of construction waste should be managed to avoid creating further instability problems because of inappropriate disposal.

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