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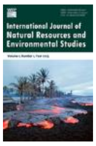

Relationship between Deformation and Epigenetic Configuration of Rock and Soil Bodies on Slopes

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ABSTRACT

The development and evolution of slopes can often destroy construction buildings, interrupt traffic, block rivers, and threaten the safety of people and animals. Therefore, it is of great practical significance to study their formation and development process and to take preventive measures. However, the surface structure often covers up some real structural appearance, so it can correctly identify the surface structure and distinguish it from the real structural deformation. It has great practical significance for geological mapping, regional structural research, analysis of hydrological engineering geological conditions, seismic geological survey and deposit exploration and mining. This paper first introduces the basic types of slope deformation and destruction and the mechanism mode of slope failure, and finally discusses the relationship between slope deformation and epinal structure.

KEYWORDS

Slope; Geotechnical Deformation; Epigenetic Configuration.

1. INTRODUCTION

Under the action of various endogenic and exogenic geological forces, the stress distribution within slope masses changes. When the strength of rock and soil masses composing the slope cannot adapt to such stress distribution, slope deformation and failure occur. Slope deformation and failure have caused numerous disasters to human society and engineering construction both at home and abroad.

On October 9, 1963, a catastrophic large-scale landslide occurred on the left bank of the Vajont Reservoir in Italy, shocking the world and claiming approximately 3,000 lives. Creep deformation of the mountain mass on the left bank was observed at the initial impoundment stage of the reservoir. As the reservoir water level rose, the pore water pressure on the sliding surface increased, triggering the overall sliding of the slope mass, and the reservoir eventually lost its function due to sedimentation by the sliding mass.

Restricted by China’s unique physical geographical and geological conditions, slope geological hazards are widely distributed, highly active and severely destructive across the country. For instance, on March 6, 1963, during the initial impoundment of the Zhexi Reservoir on the Zishui River in Hunan Province, a high-speed landslide took place on the right bank near the dam reservoir area, marking the first large-scale landslide triggered by reservoir impoundment in China. On July 13, 2003, one month after the Three Gorges Reservoir water level rose to 135 m, the Qianjiangping Landslide with a volume of 15 million cubic meters occurred on the Qinggan River, a tributary of the Yangtze River in Zigui County, Hubei Province. The landslide blocked the river and caused enormous economic losses. To prevent such catastrophic slope disasters, further research on slope deformation and failure is urgently required.

Slope structure and rock mass structure are the primary controlling factors of slope deformation and failure. Their combinations form diverse types of slope geological structures, and slopes with different geological structural types exhibit distinct deformation and failure modes. Huang Runqiu[1], Tan Linyun et al.[2] summarized five slope failure modes: sliding-tensile cracking-shear failure, toppling failure, horizontal thrust failure, bedding rock creep-sliding and tensile cracking failure, and buckling failure. Zhong Denghua et al.[3] and Zhou Depei et al.[4] clearly defined the concept of slope mass structure and distinguished the differences between slope mass structure and rock mass structure. Wang Lansheng et al.[5] and Gong Tao et al.[6] classified slope mass structures based on the structural plane characteristics of rock strata and lithological combinations of slope masses. Wang Yanrong et al.[7] and Chen Longfei[8] conducted a detailed classification of layered rock slope structures by integrating previous research findings. Li Hongwei[9] and Shen Li[10] combined slope structure types, slope mass characteristics and deformation-failure modes, classified slope structures from different rock-soil media, and summarized the corresponding disaster failure modes of each slope structure type.

This paper mainly introduces the basic types and mechanism modes of slope deformation and failure, and further discusses the relationship between the deformation of slope rock-soil masses and supergene structures. The research aims to provide a scientific basis for slope remediation and slope engineering design.

2. BASIC TYPES OF SLOPE DEFORMATION AND FAILURE

Changes in slope stress state break the original equilibrium. Local stress concentration exceeds the allowable strength of rock masses at corresponding positions, causing local shear dislocation, tensile cracking and minor displacement without overall collapse; this process is defined as slope deformation. With further development of slope deformation, failure surfaces continuously expand and connect with each other, separating part of the slope rock-soil mass and inducing large displacement, which is defined as slope failure. Slope deformation is the precursor to slope failure, while slope failure is the inevitable consequence of slope deformation.

2.1. Slope Deformation

The main forms of slope deformation include tensile cracking (rebound), creep sliding and bending toppling.

Tensile cracking refers to the deformation form where tensile fractures develop in local tensile stress concentration zones and tension bands of slope rock-soil masses. Such fractures are wider at the top and narrower downward until pinching out (Fig. 2-1). It is most commonly observed at the shoulder of high and steep slopes composed of hard rock and soil masses, and the fractures are generally nearly parallel to the slope surface. Tensile cracking destroys the integrity and continuity of slope masses and reduces rock-soil strength, forming channels for rainwater and groundwater infiltration and migration, which further loosens the slope mass. Gradual expansion of tensile cracks connects with other structural planes to form through-going failure surfaces, inducing various forms of slope failure. Although tensile cracking itself is only a deformation phenomenon, it creates favorable conditions for slope failure, and large-scale slope failures are invariably associated with the development of tensile cracks.

Creep sliding refers to the slow shear deformation of slope rock-soil masses along weak planes/layers towards the free face. In homogeneous rock-soil masses, creep sliding is generally controlled by the maximum shear stress trajectory; where weak structural planes exist, it is dominated by gently inclined weak planes dipping out of the slope. Surface creep mostly occurs in steeply inclined layered rock strata or rock masses with well-developed steep structural planes, where the strike of bedding planes or structural planes is parallel or nearly parallel to the slope strike. It tends to develop more easily in strata dipping opposite to the slope or with dip angles greater than 60°. When the slope base consists of thick weak rock-soil masses, the slope mass may undergo plastic flow extrusion towards the free face, termed deep creep[11] (Fig. 2-2), which mainly develops in the lower part or interior of the slope.

For slopes composed of steeply inclined or vertical tabular rock masses with strata strike roughly consistent with the slope strike, long-term gravitational loading causes the rock strata to bend and fracture from the front edge towards the free face and gradually extend inward the slope. This deformation is defined as bending toppling (Fig. 2-3).

In summary, slopes feature diverse deformation forms and properties. In terms of deformation continuity, tensile cracking and toppling belong to discontinuous deformation, while creep deformation is generally continuous. As slopes are composed of discontinuous media with specific structural characteristics, slope deformation is always inhomogeneous: macroscopically continuous deformation actually contains discontinuous components such as tensile cracking. Slope deformation indicates an unstable evolutionary trend, which will inevitably develop into slope failure.

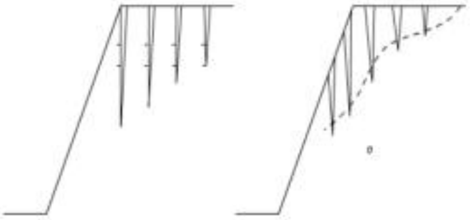

Fig 2-1 Tensile crackingFig.

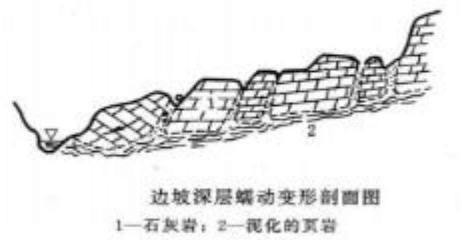

Fig 2-2 Deep creepFig.

Fig 2-3 Field phenomenon of rock strata bending and toppling

2.2. Slope Failure

Further development of slope deformation leads to the expansion and interconnection of failure surfaces, separating part of the slope rock-soil mass and generating large displacement, namely slope failure. The main failure forms are collapse and landslide.

Collapse refers to the phenomenon and process where rock blocks divided by steeply inclined tensile fracture planes suddenly detach from the parent slope mass, moving mainly vertically with rolling and jumping (Fig. 2-4).Landslide refers to the phenomenon where slope rock-soil masses move mainly horizontally along through-going shear failure surfaces/zones (Fig. 2-5). The displaced rock-soil mass is called the sliding body, and the underlying stationary rock-soil mass is defined as the sliding bed[12].

Conditions for Collapse Occurrence:

(1) Lithological condition: Thick-bedded hard and brittle rock masses. Thick hard brittle rocks such as limestone, sandstone and quartzite often form high and steep slopes. Unloading fractures develop at the slope front edge, forming steep deep tensile cracks that combine with other structural planes to form continuous through-going separation surfaces, triggering collapse under triggering factors.

(2) Rock mass structural condition: Joints and fractures. Hard brittle rocks usually develop two or more sets of steeply inclined joints, among which the set parallel to the slope surface often evolves into tensile cracks.

(3) Topographic condition: Intense terrain incision and large elevation difference. Collapses generally occur on slopes steeper than 45°, mostly on slopes with gradients over 60°.

(4) External force condition: Weathering, hydrostatic pressure, seismic vibration, frost heave, etc.

Collapses mostly occur at the shoulder of high and steep slopes, with vertical displacement components far larger than horizontal ones. They feature sudden occurrence, rapid movement and recurrence: collapsed areas are prone to secondary collapse.

Conditions for Landslide Occurrence:

Landslide formation is controlled by two major factors: geological and geomorphological conditions, as well as endogenic-exogenic dynamic forces and human engineering activities.

Geological and Geomorphological Conditions:

(1) Rock-soil type: Rock and soil masses are the material basis of landslides. Slopes composed of loose overburden, loess, lateritic clay, shale, mudstone, coal measures strata, tuff, schist, slate, phyllite and interbedded hard-soft rock strata are highly susceptible to landslides due to loose structure, low shear strength and poor weathering resistance, with properties vulnerable to water alteration.

(2) Geological structure condition: Slope rock-soil masses can slide downward only when cut into discontinuous blocks by various structural planes, which also provide channels for rainfall infiltration. Landslides readily occur on slopes with well-developed joints, fractures, bedding planes and faults, especially where steep structural planes parallel/vertical to the slope and gentle bedding structural planes dipping out of the slope are developed.

(3) Topographic and geomorphological condition: Landslides occur only on slopes with specific landform positions and proper gradients. Typical susceptible locations include slopes along rivers, lakes, reservoirs and gullies, open hillsides, and cut slopes of railways, highways and engineering buildings. Favorable landforms for landslides feature gradients of 10°–45°, with an upper steep-middle gentle-lower steep profile and annular upper slope morphology.

(4) Hydrogeological condition: Groundwater activity plays a dominant role in landslide formation by softening rock and soil, reducing shear strength, generating hydrodynamic pressure and pore water

pressure, causing subsurface erosion, increasing bulk density, and producing buoyancy on permeable rock strata. Its softening and strength reduction effect on sliding surfaces is particularly prominent.

Dynamic and Human-Induced Factors:

Landslides are concentrated in areas with active crustal movement and intensive human engineering activities. External factors alter basic landslide-forming conditions and induce sliding. Main triggering factors include earthquakes, rainfall and snowmelt, surface water scouring and immersion, river erosion at slope toes; irrational human activities such as slope toe excavation, upper slope loading, blasting, reservoir impoundment and discharge, and mining; as well as tsunamis, storm surges and freeze-thaw cycles.

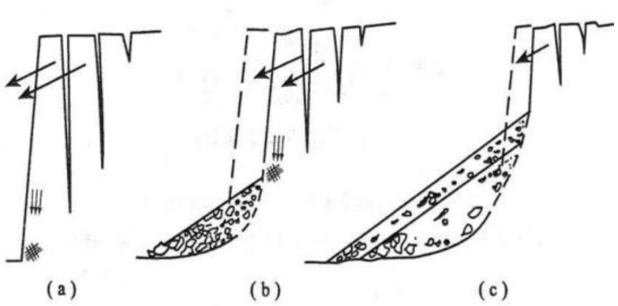

Fig 2-4 Collapse

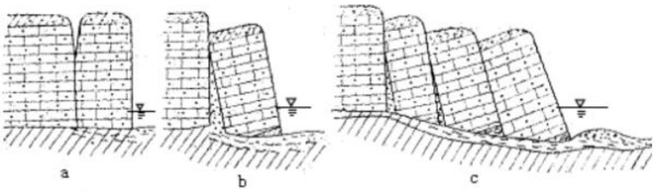

Fig 2-5 Landslide

3. MECHANISM MODES OF SLOPE FAILURE

3.1. Creep-Sliding and Tensile Cracking

This type of landslide mainly develops on soil slopes or completely/strongly weathered rock slopes with moderate gradients (below 40°). Under gravity, slope rock masses undergo shear creep towards the free face, with tensile cracks developing downward from the ground surface at the rear edge of the deformed mass. No dominant sliding surface exists within the slope; the position of the sliding surface is controlled by the maximum shear stress plane, above which a shear creep zone forms with stress decreasing downward.

With the progression of creep sliding, the slope surface subsides and tensile cracks extend downward to potential shear surfaces, inducing shear stress concentration. Surface water infiltrates along tensile cracks, accelerating creep sliding, reducing the shear strength of failure surfaces, and eventually causing shear rupture and landslide (Fig. 3-1). The evolutionary process is divided into three stages:

(1) Surface creep: Rock strata bend downhill with tensile stress generated at the rear edge;

(2) Rear edge tensile cracking: Forming reverse slope benches. Tensile cracks develop more easily where steep weak structural planes dipping inward the slope exist at the rear edge, and may occur suddenly triggered by earthquakes or blasting;

(3) Shear disturbance of potential sliding surface: Further shear deformation causes stress concentration zones in the slope middle to expand and dilate, leading to gradual uplift of the lower slope.

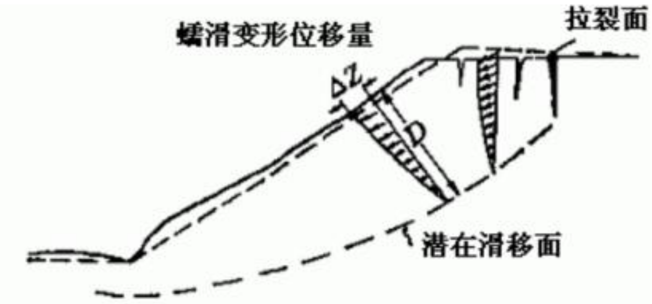

Fig 3-1 Creep-sliding and tensile cracking

3.2. Sliding-Compression Induced Tensile Cracking

This deformation mainly occurs on moderate-gradient slopes composed of gentle layered rock masses with weak structural planes dipping out of the slope. When the slope mass undergoes slow creep sliding along structural planes towards the free face due to unloading, tensile stress concentration near locking or staggered points on the sliding surface generates open fractures nearly perpendicular to the sliding surface. Tensile fractures expand upward (occasionally downward) and eventually induce landslides. The primary difference from creep-sliding tensile cracking is that sliding and tensile cracking develop upward along internal weak planes of the slope.

3.3. Sliding-Tensile Cracking

This failure mode dominates moderate-gradient layered slopes or block slopes cut by two sets of structural planes. It occurs when layered slopes contain dominant weak planes with dip angles roughly parallel to the slope surface, or when the intersection line of composite weak planes in block slopes dips out of the slope with a dip angle no less than the residual friction angle φr of the weak plane.

Controlled by pre-existing weak planes, the deformation process depends on the occurrence and properties of sliding weak planes. When the dip angle of the sliding surface is large enough to make the downslope driving force exceed the shear resistance, rapid sliding occurs immediately after tensile cracks form once the sliding surface is exposed to the free face, with an extremely short creep stage (generally when the dip angle exceeds 20°). When the dip angle approximates the residual internal friction angle and shear strength approaches the residual value, deformation transitions to slow sliding, disintegrating the slope into labyrinthine block landslides. All such deformations ultimately evolve into landslides.

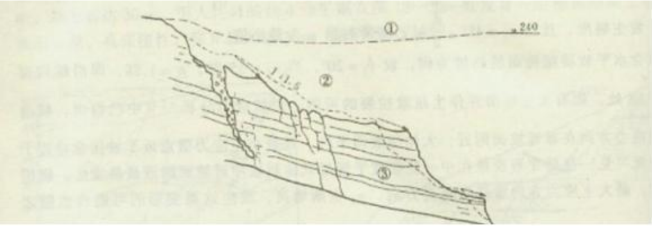

Fig 3-2 Sliding-tensile cracking

3.4. Bending-Tensile Cracking

This deformation mainly develops on steep slopes composed of vertical or inward-steep layered rock masses, with the strike angle between structural planes and the slope surface less than 30°, mostly concentrated at the slope front edge. Under bending moment induced by self-weight, steep tabular rock masses bend like cantilever beams from the front edge towards the free face and extend inward the slope, defined as toppling. Bending tabular rock strata undergo tensile cracking or mutual dislocation, forming strike-parallel grooves and reverse slope benches. The maximum bending parts of forward-tilting tabular strata are prone to fracturing. Pore water pressure in fractures, water wedging, expansion force from repeated freeze-thaw of seepage in alpine regions, and seismic vibration are major driving factors for this deformation.

3.5. Plastic Flow-Tensile Cracking

This deformation occurs when underlying soft rock undergoes plastic flow and extrudes towards the free face under the overburden pressure of upper hard rock strata, causing tensile cracking, disintegration and uneven subsidence of overlying rock masses (Fig. 3-3). It is common in soft-base slopes with weak layers/belts as the foundation. Weathering, groundwater softening, dissolution and subsurface erosion of weak bases are the main controlling factors.

For slopes with nearly horizontal weak bases, tensile cracking of overlying hard rock initiates at the contact surface of weak layers, due to far greater deformation of soft rock than hard rock. Local collapses may occur at the slope front edge, evolving into labyrinthine block landslides. When overlying strata possess certain plasticity, the rock mass carried by plastic-flow soft rock slides integrally towards the free face, with tensile cracking at the rear edge causing collapse and gradual slow sliding landslides.

For steep cliffs with gently inward-dipping weak bases, the weak base slowly extrudes outward under overburden pressure, inducing uneven subsidence of upper strata with displacement decreasing inward the slope and tensile cracking of hard rock. Tensile cracks first appear near the cliff edge and develop downward. Rock pillars divided by cracks may collapse with further extrusion of soft rock, and crack initiation positions shift from the slope edge to the rear with deep development. The lower part of tall rock pillars may be sheared and crushed, transforming the deformation into creep-sliding tensile cracking and eventually collapse-sliding landslides.

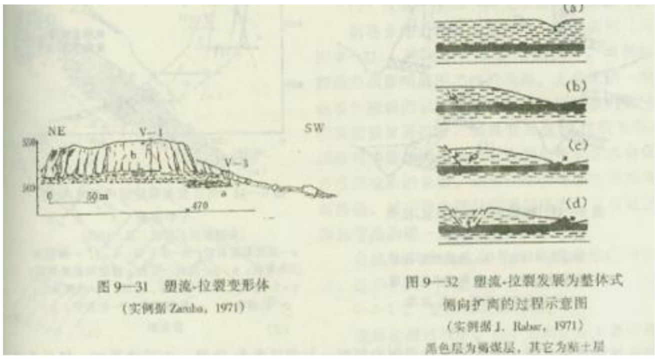

Fig 3-3 Plastic flow-tensile cracking

3.6. Sliding-Bending

Layered rock masses sliding along sliding surfaces undergo longitudinal bending deformation under compressive stress parallel to the sliding direction due to resistance at the lower part. Lower resistance is mainly caused by unexposed sliding surfaces or chair-shaped sliding surfaces (steep upper part and nearly horizontal lower part) that significantly increase sliding resistance.

Development conditions require weak planes capable of sliding to dip out of the slope with dip angles obviously larger than the residual friction angle (generally over 20°), most commonly seen in thin-bedded and flexible carbonate layered rock masses. The full evolutionary process of sliding-bending deformation with flat sliding surfaces is shown in Fig. 3-4.

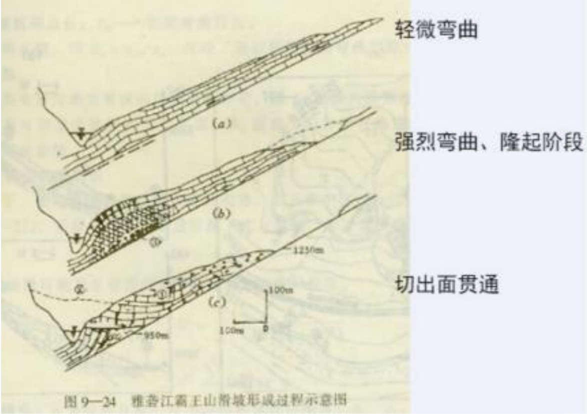

Fig 3-4 Sliding-bending

4. RELATIONSHIP BETWEEN SLOPE ROCK-SOIL DEFORMATION AND SUPERGENE STRUCTURES

Supergene structures refer to geological structures not directly formed by tectonic movements, restricted to the uppermost crust with small scale, limited development depth (usually several to tens of meters). Most supergene structures form under normal temperature and pressure, rarely accompanied by metamorphism and hydrothermal activity. They are mostly tensional or transtensional, spatially incompatible with tectonically formed structures and cannot be explained by a unified stress field.

The basic forms of supergene structures include folding and fracturing of rock strata and sediments, with simple or complex morphologies that largely control rock mass stability. Supergene structures often mask genuine tectonic features; accurate identification and differentiation from tectonic deformation are of great practical significance for geological mapping, regional tectonic research, hydrogeological and engineering geological analysis, seismic geological survey and mineral exploration.

4.1. Supergene Structures Formed by Gravitation

Such structures are formed by gravitational action on surface rocks/strata, typical types including creep structures, curling structures and landslide structures.

Gravitational creep structures on hillsides induce knee-shaped bending or even horizontal overturning of rock strata (Fig. 4-1). Long-term slow downward creep of residual and slope deposits drives bedrock creep, forming knee-shaped folds or horizontal recumbent folds, commonly developed in weak rock strata such as shale, marl and phyllite, with limited influence depth of only several meters.

Curling structures are small-scale complex folds. Although not all are gravity-induced, plastic flow under surface gravity undoubtedly forms numerous intricate small folds, often occurring in specific strata to form deformed laminae (curly laminae), also termed syngenetic microfolds due to dominant plastic bending. They are easily misidentified as interlayer folds in field work; genuine tectonic folds feature regular morphology, systematic axial surface and hinge distribution, and inherent geometric connections with regional major structures.

Fractures and weak interlayers reduce the internal cohesion of bedrock on slopes. When the slope toe is eroded by rivers or excavated artificially, rock masses lose balance and slide downward integrally along one or multiple internal sliding surfaces. Landslides vary in scale, generally tens to hundreds of meters in width, with arc-shaped sliding surfaces along joints, faults or weak planes in plane and profile views.

Slope geomorphology controls internal stress distribution and surface runoff characteristics; slope height, gradient and morphology are key factors determining sliding force. High and steep slopes/cliffs expose internal weak planes, increasing driving force, reducing anti-sliding resistance and providing sliding space, serving as critical landslide-forming conditions. Gentle, low-gradient slopes with good vegetation coverage are generally stable.

Fig 4-1 Curling structure

4.2. Supergene Structures Formed by Dissolution and Water Absorption

Dissolution-induced structures include sinkhole landslides and funnel structures. Water absorption causes gypsum volume expansion by over 40%, forming small-scale gentle upwarped folds.

The Three Gorges area develops diverse supergene structures, categorized into continuous, discontinuous and transitional types. Continuous types include goose-wing folds and toppling-bending structures; discontinuous types include dense joint zones and karst normal faults; transitional types include boudinage structures and block overturning structures. Widely distributed in the Three Gorges area, these structures are formed by karstification of marly limestone[13].

The development of supergene structures involves the loss of soluble components and enrichment of argillaceous components in rocks. Reduction of soluble components lowers rock strength and alters rock mass structure, leading to foundation quality degradation or severe deformation and failure. Fold development induces uneven ground subsidence: synclinal zones suffer intense karstification with large subsidence, while anticlinal zones subside slightly; synclinal centers are prone to landslides and debris flows under gravity due to strong dissolution. Toppling and bending of rock strata also cause uneven subsidence and foundation cracking. Dense joints loosen rock masses, induce foundation cracking and softening, and trigger landslides or collapses in severe cases. Normal faults lead to foundation cracking, landslides and collapses. Boudinage and block rotation structures cause slope deformation and failure, closely related to extensive slope collapses in reservoir excavation projects[14-15].

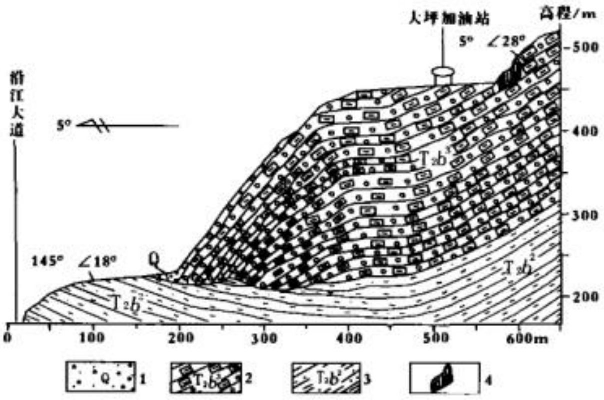

Fig 4-2 Profile of dumping and bending structure on the eastern slope of Baiyan ditch, Xincheng site, Badong County (1 Quaternary gradient; 1 three sections of Padong Formation; 3 two sections of Badong Formation; 1 dense joint belt)

4.3. Supergene Structures Formed by Differential Compaction

Differential compaction structures originate from variable compressibility of sediments, such as sandstone lenticles. Two prerequisites for differential compaction anticlines/upwarps: rigid rock masses surrounded by clay and mudstone, and overburden thick enough to compact mudstone.

Compaction is a deformation effect induced by burial loading, a natural adaptation to vertical stress, analogous to pressing a brick on wet sponge: water extrusion reduces porosity, increases density and decreases thickness. Differences in sediment grain size and composition lead to variable compaction strain, namely differential compaction. Simple compaction only causes volume strain with thinning and volume reduction of sedimentary layers.

Typical differential compaction structures include suprathin folds, apical thin folds, fish-tail structures, shrinkage-expansion structures and faults. Suprathin folds differ from apical thin folds: they form when soft sediments overlie buried monadnocks, buried hills or reefs, or low-compressibility sandstone lenticles. During diagenetic compaction, thinner soft sediments over monadnocks experience less compaction than thicker basin sediments, causing strata to bend downward at monadnock margins and form suprathin folds, which are significant for petroleum geology as buried hill and monadnock tops are favorable hydrocarbon accumulation sites.

Fish-tail structures are intercalated interbedding at lithological boundaries, commonly developed in coal measures strata. Peat formed in swamps is interlayered with fluvial and marsh margin sandy deposits during compaction, dividing thick coal seams into thin horizontal layers and forming fish-tail structures.

5. CONCLUSION

Slope deformation and failure represent two distinct evolutionary stages of slope masses: deformation is the quantitative change stage, while failure is the qualitative change stage, constituting a cumulative damage process.

Slope stability analysis requires qualitative identification of triggering mechanisms first, followed by reasonable quantitative engineering calculation based on accurate causal understanding. Rational qualitative analysis and modeling lay a foundation for establishing mechanical calculation models and numerical simulation models, enabling calculations and simulations to accurately reflect actual slope conditions. Therefore, the deformation mechanism of slopes plays a fundamental role in the research and prevention of slope geological disasters.

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