Reactivated ancient slides at the Sungai Kelalong Dam site, Bintulu Sarawak, East Malaysia

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Abstract: The Sungai Kelalong Dam site is founded in the interbedded mudstone-sandstone of the Miocene age Nyalau Formation. The formation has been mildly deformed and resulted in very broad, open syncline-anticlinal folds plunging in the South to Southwest direction. The rock masses are dissected by at least 4 sets of discontinuities, mainly the bedding planes, joints and faults. The occurrence of massive landslide on the spillway slope and part of the neighbouring core trench wall was largely attributed to the intersection of low angle, listric normal fault and the subvertical, E-W striking fault zone. The former is interpreted as a sliding plane of an ancient slide, which probably took place during the Pliocene uplifting in a condition of wet soft sedimentary deformation, to allow for the formation of well-developed normal listric faults system. Reactivation of the ancient slide is caused by the extensive earthworks activities for the dam construction which resulted in massive landslide to the spillway slope. This case study gives clear examples of the importance of geological inspection during the construction stage to check and to detect any structural defects that were not identified in the previous site investigation works.

Abstrak: Tapak pendasaran Empangan Sungai Kelalong, Bintulu, Sarawak terdiri daripada selang lapis batu lumpur dan batu pasir Formasi Nyalau yang berusia Miosen. Batuan Formasi Nyalau ini tercangga lemah dan terlipat dalam bentuk sinklin-antiklin yang sangat landai dan paksinya menjunam dalam arah Selatan – Barat Daya. Ketakselanjaran pada jasad batuan di kawasan ini dibentuk oleh satah-satah perlapisan, kekar, sesar dan zon sesar. Kejadian tanah runtuh di bahagian cerun alur limpah dan sebahagian daripada parit teras empangan dipercayai berpunca daripada persilangan di antara sesar normal listrik bersudut-landai dengan zon sesar curam yang berjurus hampir T-B. Satah sesar listrik itu dipercayai merupakan satah gelinciran kepada sebuah gelinciran kuno yang dipercayai terbentuk semasa Pliosen dalam keadaan canggaan ketika sedimen masih basah dan lembut, yang mana membolehkan terbentuknya suatu sistem sesar normal listrik yang baik. Pengaktifan semula gelinciran kuno ini disebabkan oleh aktiviti-aktiviti kerjatanah semasa pembinaan pendasaran alur limpah dan empangan utama. Kajian kes yang dipersembahkan ini jelas menggambarkan betapa pentingnya kerja-kerja penyiasatan geologi semasa pembinaan untuk menentusahkan kehadiran sebarang unsur-unsur kecelaan geologi yang tidak dapat dikenalpasti semasa penyiasatan tapak sebelum pembinaan.

INTRODUCTION

Sungai Kelalong Dam is located approximately 20 km northeast of Bintulu, Sarawak and forms part of the Bintulu Water Supply Stage III project. The main stream is locally named as Sg. Kelalong, tributary of the Sungai Sibiu. The main stream is a 10 m wide shallow stream that flows west before turning abruptly south to eventually join Sungai Sibiu. The dam site is located at about 600 m south of the above mentioned abrupt turn in flow direction (Figure 1). Access to the proposed dam site itself is by way of an upgraded logging track which branches off from Km 18, Rumah Mujah, Bintulu – Miri trunk road. The construction of the dam began in early 2002 and it is expected to be completed in mid 2004.

This paper presents a classical example of an occurrence and field recognition of an ancient slide (probably submarine) which was reactivated by current engineering activities. Reactivation of the ancient slide resulted in a massive slope failure (landslide) to the foundation site of the proposed spillway and part of the main dam. The presence of the ancient slide was detected during geological mapping which was specially arranged in June 2002. The original intention of the mapping was to investigate the caustive factor for the major landslide which occurred at the spillway foundation and the core trench wall of the main dam between CH650 and CH730. Having done detailed mapping, it was found that the landslide was primarily due to the presence of the ancient slide, in which its basal fault plane intersected with another subvertical major fault striking almost E-W. This case study is an example where detailed geological mapping is very important to extract vital geotechnical information, which could not be identified from subsurface investigation (boreholes).

In this study, the strength and consistency of the rocks and soils were estimated based on guidelines by the ISRM suggested methods (Brown, 1981). The weathering grades of the rock masses were described based on the IAEG classification scheme which was refined by Attewell (1993).

GEOLOGY OF THE BINTULU AREA

The regional geology of the Bintulu area, as a whole, is well documented in Khoo (1968) and the stratigraphy is summarised in Table 1. The oldest rocks, known as the Biban Sandstone Member of the Nyalau Formation, are of Lower Miocene age, and consist of hard sandstone with subordinate shale and some limestone. The rest of the overlying Nyalau Formation is of Miocene age, about 3,000 m thick, and consists of mudstone and sandstone with coal seams and some limestone. These sediments were deposited under shallow-water marine conditions,

Table 1: Stratigraphy of the Bintulu area (after Khoo, 1968).

AGE AND LETTER CLASSIFICATION			SEDIMENTARY ROCKS	DIASTROPHISM AND CONDITIONS OF DEPOSITION
QUATERNARY	HOLOCENE		Coastal, deltaic and riverine alluvium, mainly sand, silt, clay and peat	Deposition of alluvium Eustatic sea level changes Continued Erosion
	PLEISTOCENE		Terrace alluvium, mainly sand and silt, with some quartz gravel	
TERTIARY	PLIOCENE	T_{gh}	Unconformity	Erosion followed by uplift Folding with some faulting
	MIOCENE	T_f	Sediments of Tf age may have been deposited and subsequently removed by erosion	
		Te_5	SETAP SHALE FORMATION: mainly shale and subordinate sandstone	Shallow water marine deposition
		Te_{1-4}	NYALAU FORMATION : sandstone, mudstone, siltstone and coal seams, and thin lenses of limestone. BIBAN SANDSTONE MEMBER at the base consists of hard sandstone and subordinate shale, with some thin lenses of limestone.	Fairly rapid subsidence accompanied by shallow water marine deposition, and paralic deposition in places

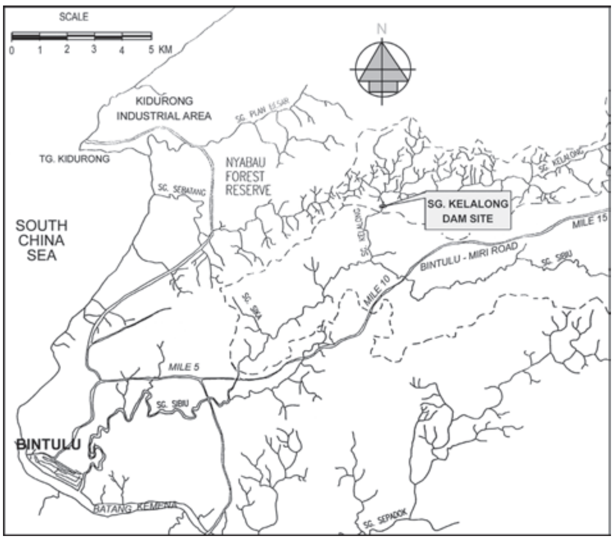

Figure 1. Map showing the geographic location of the Sungai Kelalong Dam site, Bintulu Sarawak.

but the occurrence of coal seams suggest that coastal swamps or deltaic conditions also developed locally at times.

The Nyalau Formation is overlain conformably by, and probably in part interdigitates with the Setap Shale Formation. The Setap Shale is also of Miocene age (Te_{1-4} to Te_5).

The rocks have been affected by slight to moderate folding, accompanied by faulting, which took place probably in Late Pliocene times. The major folds axes trend E-NE and the folds are mainly in the form of very gentle open synclines-anticlines.

The Pliocene folding was followed by uplift which raised most of the area above sea level in Late Pliocene times, and prolonged erosion reduced much of the area to a peneplain. Subsequent uplift and further erosion, probably in the Early Pleistocene, caused further erosion and dissection of the peneplain. The rise of sea level in the order of 40-60 m, resulted in the formation of marine and fluvial terraces. Successive eustatic sea level changes in the late Pleistocene caused the lower terraces to be built, now at about 3-7 m above sea level. In recent times, sand silt and clay were deposited in river valley and coastal regions, and extensive peat swamps have formed.

The drainage pattern of the Bintulu and surrounding areas is characterized by subdendritic to sub-trellis patterns, which suggests structural control, notably by the bedding plane orientation as well as fold culminations. Negative lineaments occur mainly in NNE-SSW, NW-SE and some E-W directions.

SITE GEOLOGY

The general geology of the site is given in detail in Tajul Anuar Jamaluddin (2003). In general, the site consists of sedimentary rocks of the Nyalau Formation, of Miocene age. The formation consists predominantly of mudstones interbedded with thin fine to medium-grained sandstones and siltstone.

Lithology

Mudstones

The mudstones are mainly bluish grey, grey to dark grey in colour. They occur mostly as beds from 1 cm to 1.5 m and are typically grey to dark grey and generally weathered to pale grey, bluish grey, grey brown or buff. In most of the outcrops, the mudstones are interbedded with light-coloured sandy shale and grey fine-grained sandstone. In places the mudstone layers contain beds of hard bluish grey, fine-medium grained sandstone from 2-10 cm thick.

Carbonaceous materials and plant remains are common, occurring either as finely disseminated flecks throughout the mudstone or as thin laminae along bedding planes. Bioturbation structures are abundant in some beds, occurring either as subvertical, inclined burrows or grazing tracks on the bedding planes.

The geology at the site is dominated by mudstones and mudstone-dominated sequences. Their occurrence can be easily recognised by their distinct dark-coloured clayey soils, once the overlying residual soils are stripped off the ground.

Sandstones

The sandstone generally occurs as beds from several cm to 0.5 m thick, interbedded with shale and siltstone or sandy shale. The sandstone is soft to moderately hard, grey to bluish grey, greyish white and fine to medium-grained sandstone.

In the lower part of the formation, the sandstone beds are often thicker and reach up to 1.5 m thick, massive sandstone. However in the upper part of the formation, the sandstone beds tend to be thinner in the order of several to tens of centimeters, where the proportion of mudstone is much more than the sandstone. Cross bedding and cross lamination are common in some sandstone beds, notably at the Diversion Culvert excavation area. A few beds show slump bedding and ripple marks.

The sandstones are lithic sandstone, and according to Khoo (1968), most of them fall in the quartzose subgreywacke class, containing between 10-25% unstable constituents (rock fragments and feldspars). The typical sandstone is a fine-grained, moderately sorted rock, consisting essentially of subangular to sub-rounded grains mostly between 0.15 and 0.25 mm across. Fine-grained carbonaceous material is common on bedding planes in some laminated sandstone, and sometimes shale flakes are lying subparallel to the bedding plane.

Structures and discontinuities

The rocks in the dam site have been slightly deformed into a series of very gentle, open, syncline-anticline folds whose axes are plunging very gentle towards south to south-southwest. The bedding planes are generally very gently dipping (5° -10°) to the SSW, SW and WSW (Table 2).

The dam site is cut by a number of NE-SW and NW-SE trending lineaments which can be inferred as major joints or fractures. The rock mass along these lineaments are generally highly sheared and the weathering profile suddenly thicker than the less dissected counterparts.

In addition to the bedding planes (B), the rocks in the study area are also affected by at least 3 major sets of joints, i.e. J1, J2 and J3. Set J1 and J2 have a steep dip towards ESE and NNE, respectively. While Set J3 commonly has subvertical dip and strikes in ESE-WNW direction. The other two sets of joints (J4 and J5) commonly occur as impersistent, tight, minor and locallised joints. Average orientations of these discontinuities are summarised in Table 2.

Weathering

Grade VI materials or residual soils are generally about 1.5 to 2.5 m thick, and consist predominantly of soft to firm, light yellowish brown to yellow, clayey to silty fine SAND and silty CLAY. The residual soil is typically yellowish-coloured and can be readily distinguished from the underlying dark-coloured grade V and grade IV materials by its colour contrast and relatively homogenous texture. Grade V materials or completely weathered (CW) rocks, consist predominantly of firm to stiff grey, light reddish brown clayey SILT or loose to medium dense reddish yellow and orange silty fine SAND. Reddish coloured soils of Grade V materials often contain some amount of iron-oxides or lateritic gravels.

Grade IV materials or Highly Weathered (HW) rocks often consists of extremely weak to very weak rocks. The profile thickness varies between 4 and 6 m. The hand specimens can be crumbled with bare hands or broken with a single firm blow of geological hammer. These HW rocks are distinguished from the above by its rocky appearance, where original rock fabric and relict structures are well preserved and clearly visible with the naked eye.

Grade III materials or moderately weathered (MW) rocks, are commonly encountered at about 8 – 9 m below the original ground level. In general, Grade III materials are characteristically, weak to medium strong rock, cannot be broken with bare hands and require firm blows of geologist hammer to break the sample. Grade II (slightly weathered) rocks are only exposed in deep excavation, normally more than 7-9 m below the original ground level. Grade II rocks are generally medium strong to strong rocks. Grade I (Fresh or Unweathered) rocks were not exposed at the dam site during the course of this study.

Table 2 : Summary of the discontinuity data from the Sg. Kelalong Dam site.

Site		No. of Reading	Average Orientation (Strike & Dip)						
			Bedding	Set J1	Set J2	Set J3	Set J4	Set J5	Set J6
Whole Dam Site		245	130/9	020/75	295/75	114/86	180/85	060/42	245/80
Diversion Channel (Left Bank Cut Slope)		25	102/9	010/65	297/66	-	-	-	-
Main Dam Foundation Site	Diversion Culvert	33	125/9	010/80	277/48	-	192/88	063/47	-
	Spillway	14	167/13	033/80	310/80	-	232/63	-	-
	CH 530 – CH580	22	124/11	020/75	300/88	115/88	194/85	-	-
	CH630 – CH665	32	153/13	028/70	306/81	136/90	-	-	-
	CH650 – CH750	33	099/7	001/65	290/80	110/88	-	-	-
	CH880 – CH950	38	120/10	353/88	-	-	175/84	064/44	242/80
Cut - Off	CH950 – CH1360	47	125/12	352/88	-	092/88	212/75	-	260/82
Notes on the Discontinuity Properties			Very closely to moderately widely spaced, tight to opened; very high persistency, smooth – undulating surfaces, wet to dry,	Major joints, moderate-widely spaced, tight, high persistency, planar, smooth to slickensided surfaces, iron coated at shallow depth, generally dry	Major joints, moderate-widely spaced, tight, high persistency, planar, smooth to slickensided surfaces, iron coated at shallow depth, generally dry	Widely spaced, tight to very tight, low persistency, planar, smooth to rough surfaces, iron oxide –coated surfaces at shallow depth, generally dry. Also included the major E-W trending faults.	Minor & localized joints, impersistent, very widely spaced, tight, planar, rough surfaces, iron oxide coated or clean surfaces, dry.	Minor & localized joints, impersistent, very widely spaced, tight, planar, rough surfaces, iron oxide coated or clean surfaces, dry.	Localised joints. Major joints in the left abutment hill, highly persistent, widely spaced, rough-undulating surfaces, often infilled with iron-oxides. Could be wet during rainy seasons.

Figure 2. View of the early-planned foundation for the spillway. The bedrock is predominantly thinly bedded mudstone-siltstone interbedded with thin fine sandstone (camera facing upstream, June 2002).

THE SPILLWAY FOUNDATION

The spillway foundation, measures about 30 m wide and 195 m long and was excavated into thinly interbedded mudstone and fine sandstones. Along the entire length of the spillway axis, the predominantly grade III rock mass is very gently dipping (5°-10°) to the SSW (Figure 2). Grade IV, V and VI rocks are only exposed in both the left and right side walls of the spillway channel.

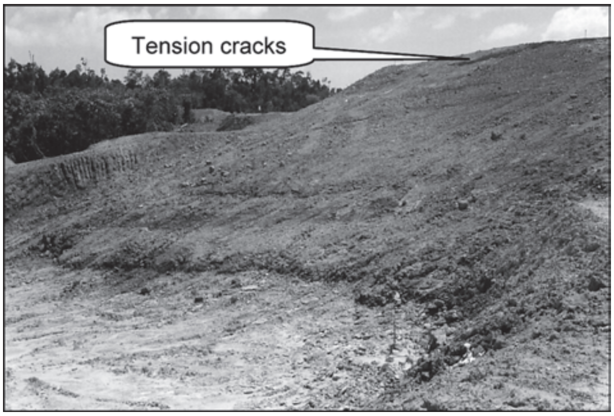

Figure 3. Bulging along the toe of the spillway slope – a clear evidence for slope movement.

Figure 4. The failure scarp of the landslide on the spillway slope.

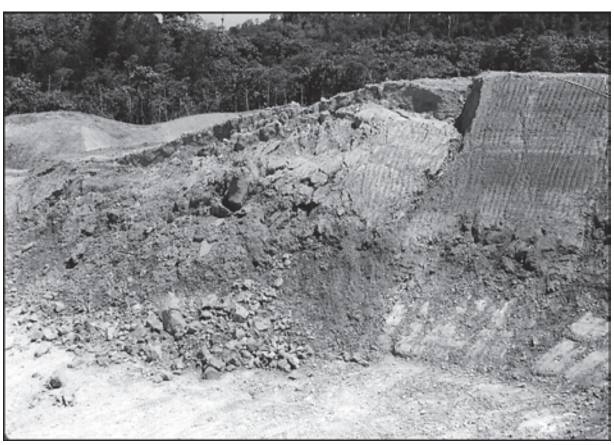

Figure 5. Side view of the same landslide which also badly affected the core trench wall of the main dam foundation.

THE SPILLWAY SLOPE FAILURE

The spillway slope failure took place at the end of May 2002 in the form of massive landslides after a few days of prolonged rainfall. The failure affected almost two-third of the spillway slope (Figures 3 & 4) and also badly damaged part of the neighbouring core trench wall of the main dam (Figure 5). On the spillway side, the landslide resulted in a marked toe bulging (Figure 3) and widely open (up to 30 cm wide) tension cracks associated with measurable vertical drops (about 20-30 cm) that

Figure 6. Close-up plan view of the closely spaced, open and sub-parallel fractures within the E-W striking fault zone, along which the tension cracks and the rear sliding plane for the failure were developed.

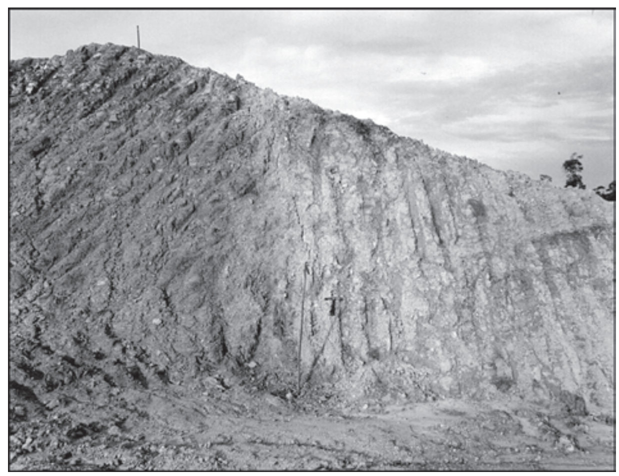

Figure 7. Note the sharp and sudden contrast in the weathering profile which indicate the profound structural control by the major fault zone referred to in Figure 6.

dissected the upper slope and spillway crest in an almost E-W direction (Figure 4). The tension cracks can be traced for more than 50 m in length along strike and was actually developed along a major fault zone striking almost E-W. The fault zone itself is characterised by a 20-25 m wide belt of subvertical open fractures (Figure 6) and sheared rocks, often filled up with reddish brown iron oxides and lateritic materials, running subparallel to each other in 095-110° direction as seen on the floor of the right wing dam foundation between CH650-CH680. The fault zone is also marked by a sudden change in the weathering grade of the rock mass as seen in the nearby excavation wall (Figure 7). The rear scarp of the landslide and the associated tension cracks were actually developed along this subvertical fault zone.

On the left of the spillway, the same landslide has also badly affected the core trench wall of the main dam foundation. The landslide looks more severe on the core trench wall because the cut face is steeper (about 80°) than the spillway slope (about 22°). Viewed from core

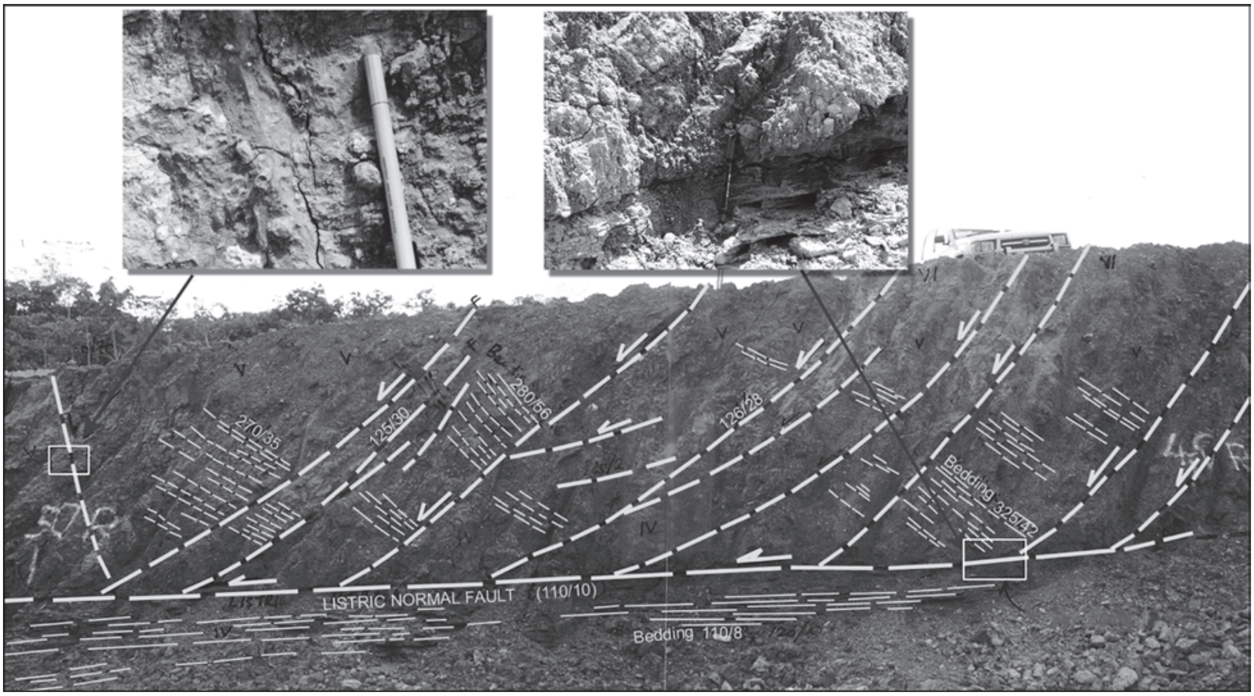

Figure 8. A major low-angle listric normal fault as exposed in the right wall of the Spillway excavation site. Insets show the close-up view of the individual fault plane.

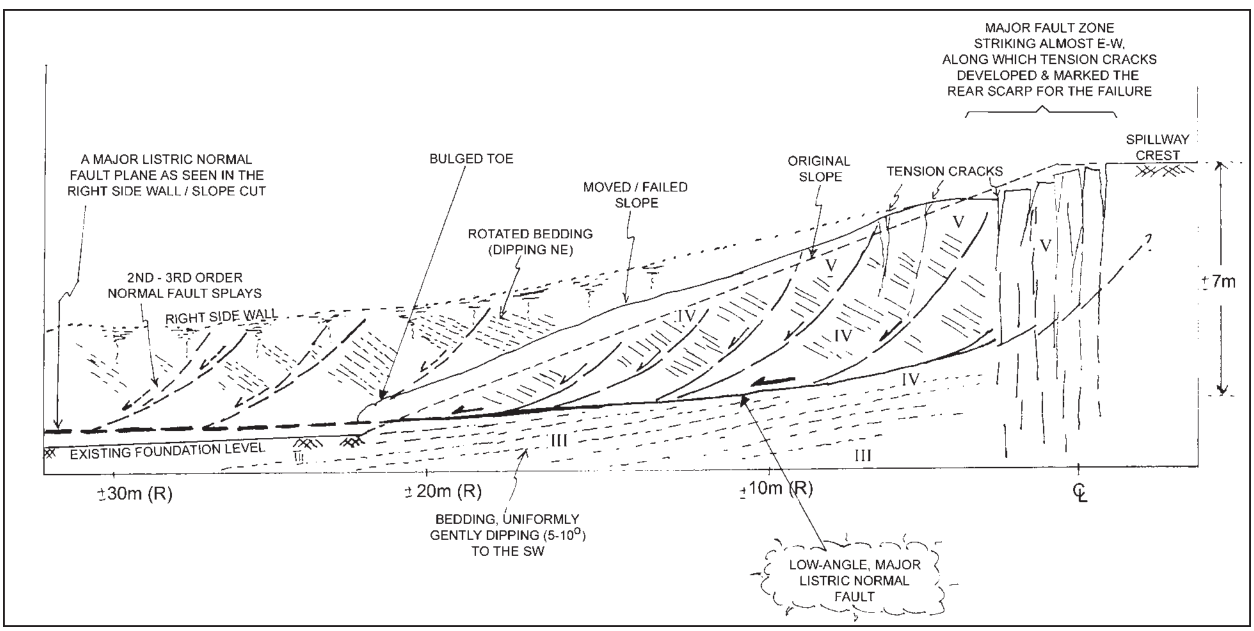

Figure 9. An idealised sketch (not to scale) showing the interpretative geological section along the Spillway axis. The slope failure is attributed to the presence of a major, low angle listric normal fault (an old sliding plane) which intersecting with the subvertical E-W fault zone.

trench side (Figure 5), the failure scarp can be clearly seen bounded by the subvertical E-W fault zone described above.

CAUSATIVE FACTORS – REACTIVATED ANCIENT SLIDE

A special post-mortem fieldwork was conducted in early June 2002, about a week after the failure took place, to investigate the causes for the landslide. Based on close inspection, it was found that the site of the spillway foundation is located within a package of an ancient slide, which has been totally weathered into grade IV to grade VI materials. This is evident by the presence of a major, low angle, basal sliding plane which resembles much of a "listric normal fault" system as shown by McClay & Ellis (1987) in their experimental analogue modellings.The listric normal fault plane is oriented subparallel to the bedding planes, and it was encountered just a few dm above the spillway floor level (Figure 8).This basal fault,

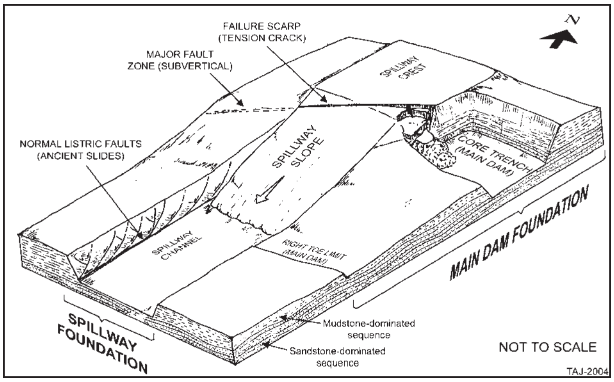

Figure 10. An idealised 3-D sketch to show the overall picture of the massive landslide which badly affected the Spillway foundation.

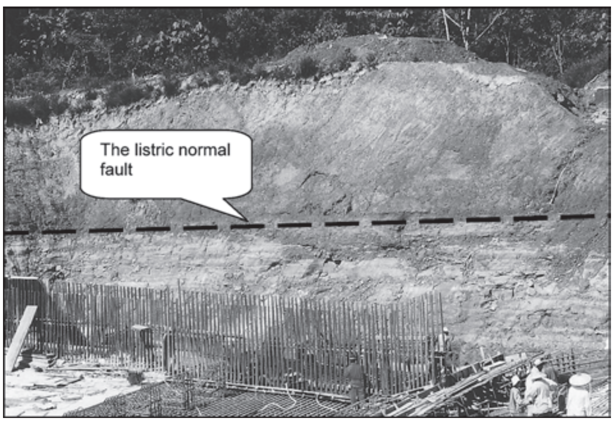

Figure 11. View of the right wall of the Spillway. Note the level of the problematic listric normal fault with respect to the current Spillway foundation level.

which represents a relict sliding plane; is well exposed on the right-side wall of the spillway channel and is marked by about 10 cm thick band of sheared rocks. Above the basal fault, the rocks are highly disturbed and tilted due to fault block rotation, showing marked contrast with the bedding below the basal fault. Above the basal fault, the bedding planes are moderate to steeply dipping towards N-NE and are dissected by numerous smaller normal (antithetic and synthetic) faults. These antithetic faults and the smaller fault splays are syn-tectonic and linked to the underlying major listric normal fault plane.

The weathering profile above the listric fault is rather highly irregular compared to the less dissected counterparts, due to preferential weathering along the structural discontinuities. Whereas below the listric fault, the rocks are generally of uniformly bedded, gentle dip and “undisturbed”. During the field inspection, a number of seepages were observed along this major listric fault. This suggests that the fault planes served as effective pathways for the infiltration of percolating groundwater, which undoubtedly substantially reduced the shear resistance of the spillway slope.

The listric fault plane can be traced upstream on the right side wall for about 70-80 m and suddenly loss of track under the spillway slope and the failed mass. It is strongly believed that this fault intersected with the subvertical fault zone described earlier, resulted in the formation of unfavourable massive wedge for the sliding to occur (see Figure 9) . The listric normal fault plane, once probably acted as a sliding plane of an ancient submarine slide, has now become reactivated by the current engineering activities in this area. This explains why the slope movement primarily took place in the spillway downstream direction rather than towards the core trench slope cut on the left, even though the spillway slope is much gentler (about 22°) compared to the core trench slope cut (about 80°). The whole picture of the slope failure is illustrated in a block diagram shown in Figure 10.

REMEDIAL MEASURES

Due to the massive failure on the spillway slope, the preliminary design of the spillway was revised. In the revised design, the foundation level was excavated deeper into grade II – grade III sandstone-dominated sequence, well below the level of influence of the listric fault and thus the potential for slope instability caused by the presence of this fault can be greatly minimised. The sandstone is generally light grey to creamy white, thinly bedded, sometimes contain very thin dark/black laminations of carbonaceous material/flakes. The bedding attitude in general dipping 10-12° to SSW. The sandstones are generally medium strong to strong rocks (Tajul Anuar Jamaluddin, 2003). Figure 11 shows the level of the listric fault with respect to the final level of the spillway foundation as in the revised design. Without the influence of the listric normal fault, the subvertical E-W striking fault alone is less likely to cause instability to the spillway slope.

CONCLUSIONS

The major landslide which affected the spillway and part of the neighbouring core trench wall of the Sg. Kelalong Dam is attributed to the presence of a major low-angle listric normal fault which intersecting with the subvertical fault zone striking almost E-W. The low-angle listric fault is interpreted as a sliding plane of an ancient slide. The ancient slide probably took place during the Pliocene uplifting and folding (Khoo, 1968), in a shallow-water environment, perhaps in a condition of wet, soft sedimentary deformation to allow for the formation of well-developed listric normal fault system. Since then, the whole landslide package was preserved and weathered in-situ and partly eroded away. The long “dormant” ancient slide has been reactivated by the impacts of extensive earthworks activities during the construction of the spillway and core trench of the Sg. Kelalong Dam.

This case study gives an example of where geological defects can only be detected by detail mapping and close on-site inspections. In this particular case, the profile of the ancient slide resembles much of the listric normal fault models of McClay & Ellis (1987). The occurrence of the old landslide was not recognized during the design stage even though a number of boreholes and subsurface investigation (trial pits) were carried out. This case study gives a clear example of how geological inspection during construction is vitally important to check on preliminary interpretations and verify any discrepancy in geological structures that have not been detected during the previous site investigation works.

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