Geological investigation and the influence estimation of WuShentou Dam via LiuChia fault

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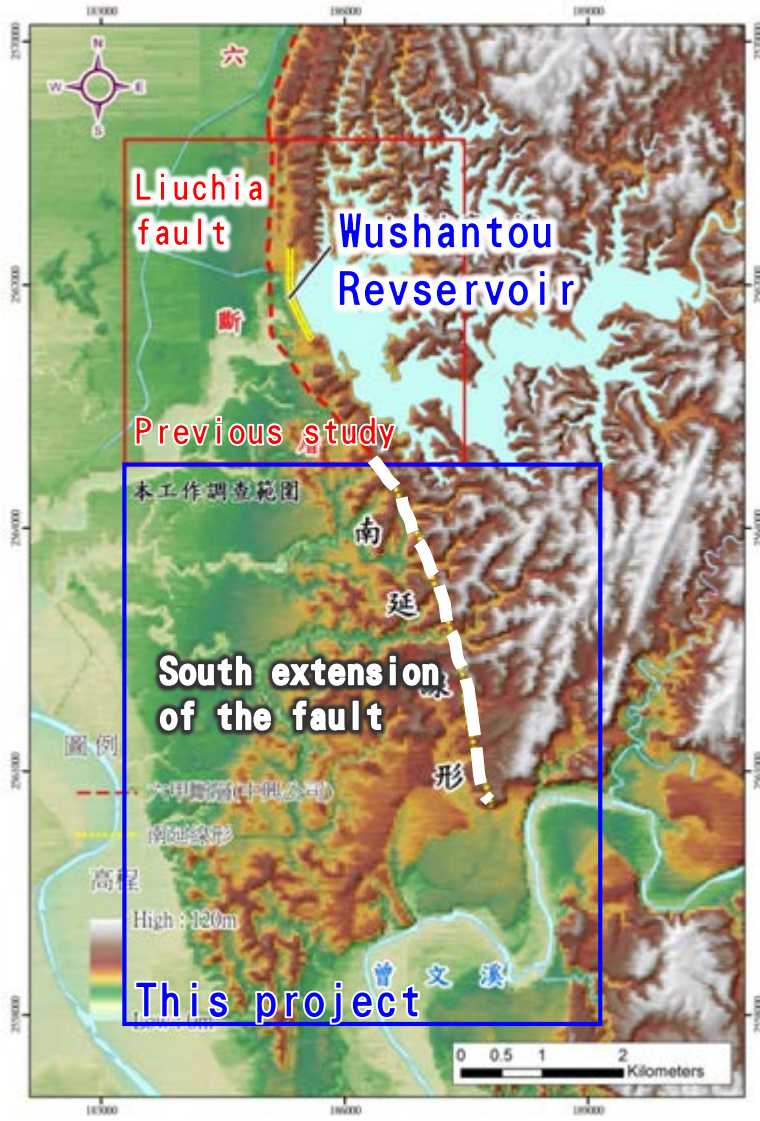
Purpose

Origin of the project:

1) Base on the results of 2015, it presented that the Liuchia fault trace might be extended to the south part, but lacking geological evidence.
2) Lacking of parameters for seismic safety assessment of the Wushantou Reservoir.

Purpose:

1) Continue the previous project work, such as geological survey, safety assessment of the Dam and stable analysis of the dam, etc.
2) Clarify the unknow parameter of the Liuchia fault, and propose an dam reinforcing assessment in order to make the dam safety qualify.



Yoichi Hatta

Yoichi Hatta

From Wikipedia, the free encyclopedia

あ→A This article **may be expanded with text translated from the corresponding article in Japanese**. *(February 2009)* Click [show] for important translation instructions. [show]

Yoichi Hatta (八田 與一, *Hatta Yoichi*, February 21, 1886 – May 8, 1942) was a Japanese engineer, known for his contributions in hydraulic engineering in the Japanese-ruled Taiwan. Hatta was born in Kanazawa, Ishikawa. After graduating from Tokyo Imperial University in 1910, he joined the Seat of Governor-General of Taiwan, served as a technician of the government. He was the designer of Chianan Canal and Wusanto Reservoir.[1]

He was killed on board the transport ship Taiyō Maru, when it was torpedoed and sunk on May 8, 1942 by US submarine *Grenadier*.[*citation needed*]

In contemporary Taiwan he is honored as a deity for his contributions to irrigation.[2]


Yoichi Hatta


Wusanto Reservoir

See also [edit]

- Pattenrail! ~ Minami no Shima no Mizu Monogatari

References [edit]

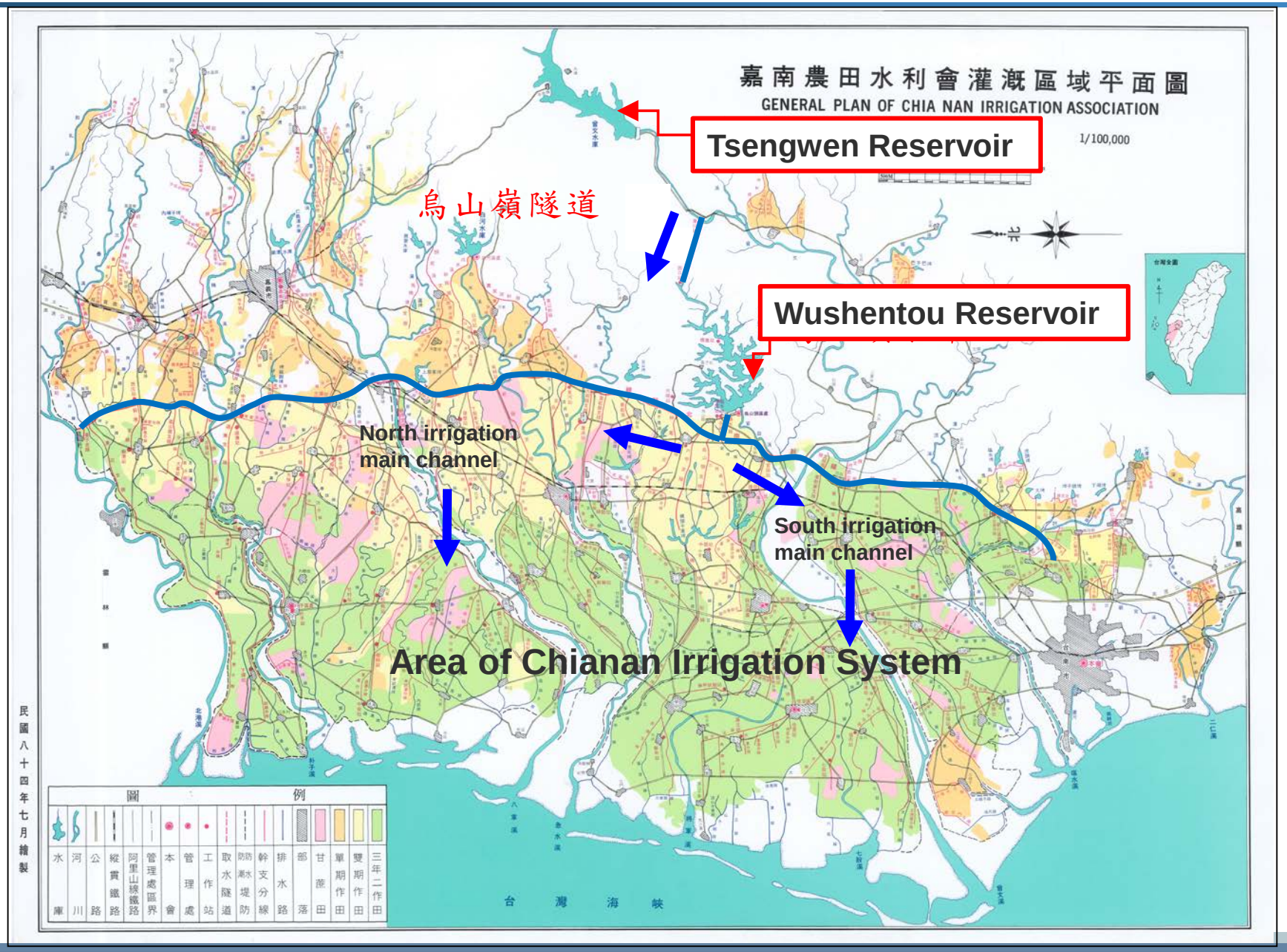
1. ^ Han Cheung (5 May 2019). "Taiwan in Time: The colonial water master". *Taipei Times*. Retrieved 5 May 2019.
2. ^ Hale, Erin. "Taiwan faces water wake-up call as climate change intensifies". *www.aljazeera.com*. Al Jazeera. Retrieved 20 August 2021.

External links [edit]

- 八田與一アーカイブス - Japan Society of Civil Engineers, JSCE Library
- Yoichi Hatta bio

Yoichi Hatta

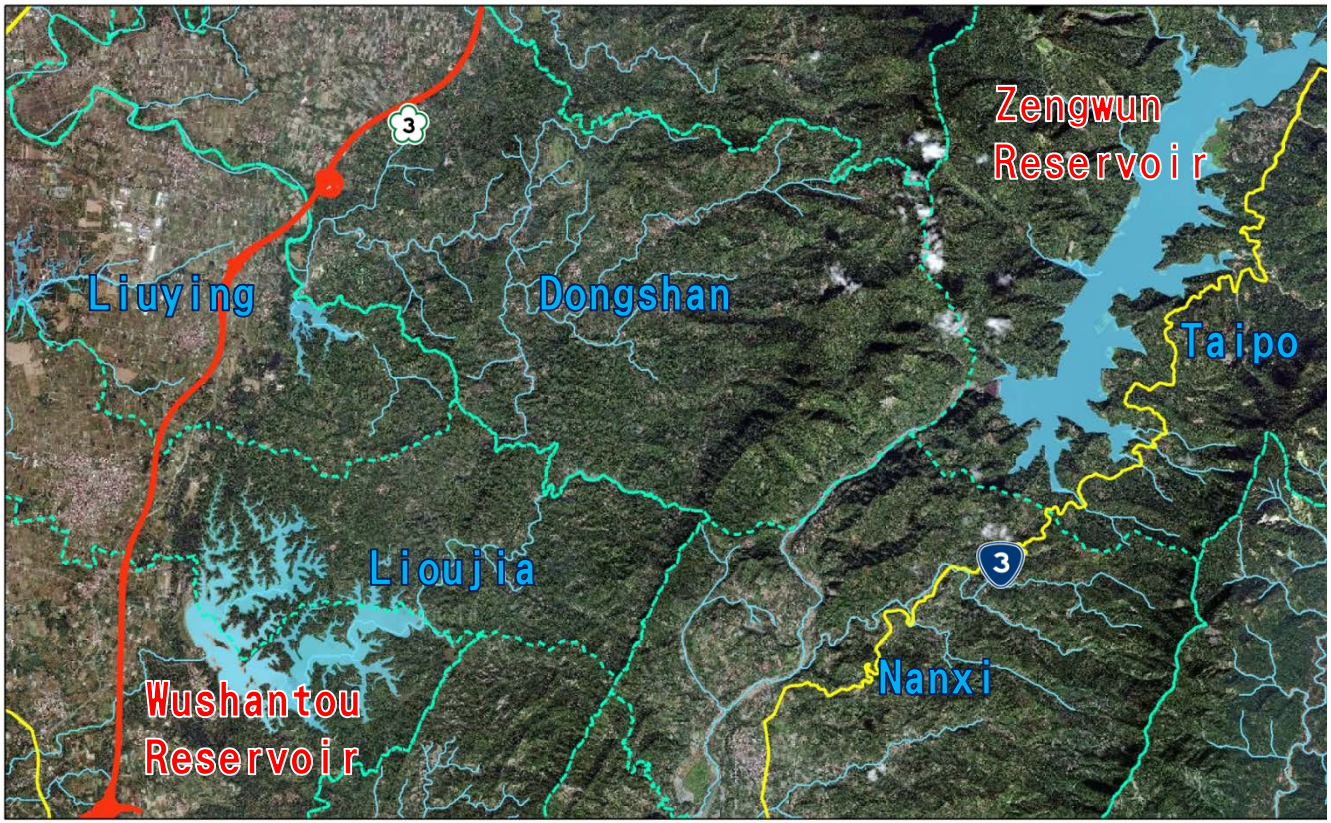
Chianan Irrigation System



Wushantou Reservoir

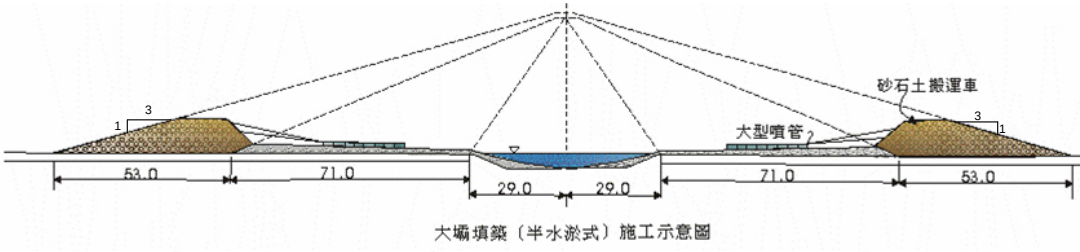
- Wushantou reservoir is a off-stream reservoir, which is located at tributary of Zengwun river. Construction was started in 1920 and completed in 1930.
- Operated in series with Zengwun reservoir since 1974.
- Change from single-target (irrigation) to multi-target operation reservoir.

River System	Mainstream：Zengwun river Tributary：Guantian river
Catchment Area	77.61km^2
Normal Conservation Level	EL.58.18m
Total Storage	154,158,000m^3 (original designed)
Dead Storage Level	EL.31.20m
Effective Storage	78,280,000m^3
Type	Semi-hydraulic fill dam
Crest Level	EL.66.66m
Height of Dam	56m
Crest Width	9m
Bottom Width	306m
Crest Length	1,273m
Volume of dam	5,400,000m^3

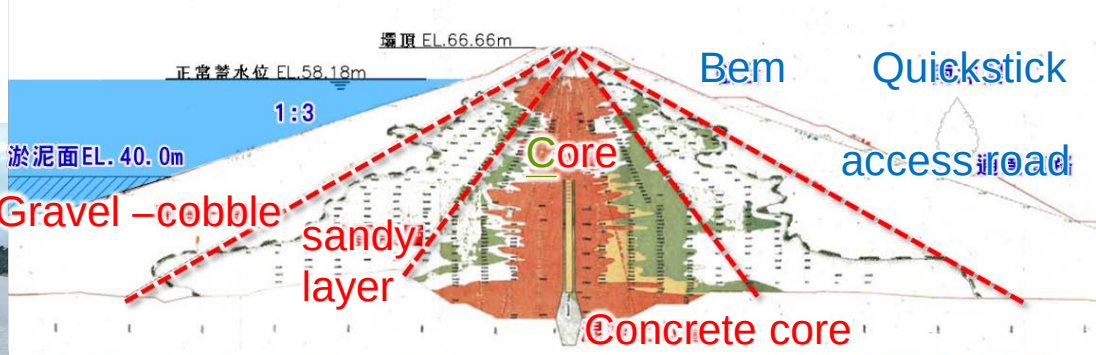


Wushantou Dam

- Type：Semi-hydraulic fill dam
- Crest Level：EL.66.66m
- Height of Dam ：56m
- Crest Length：1,273m
- Crest Width：9m
- Dam's volume：5,400,000m^3



Upstream slope condition



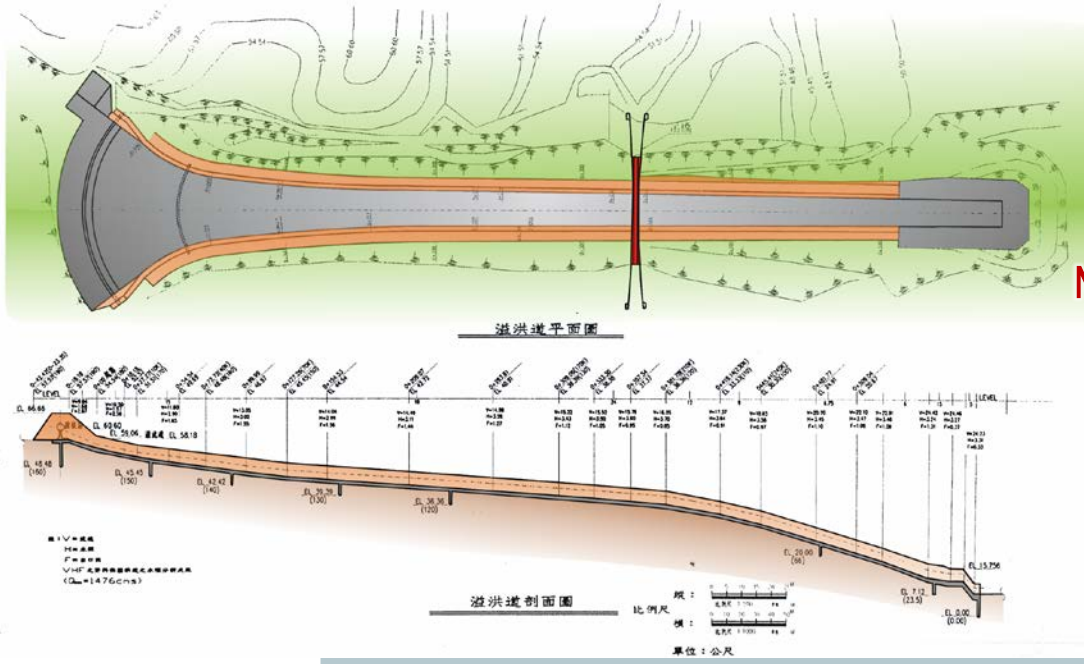
Improvement of downstream slope

Wushantou Dam

Wushantou Spillway

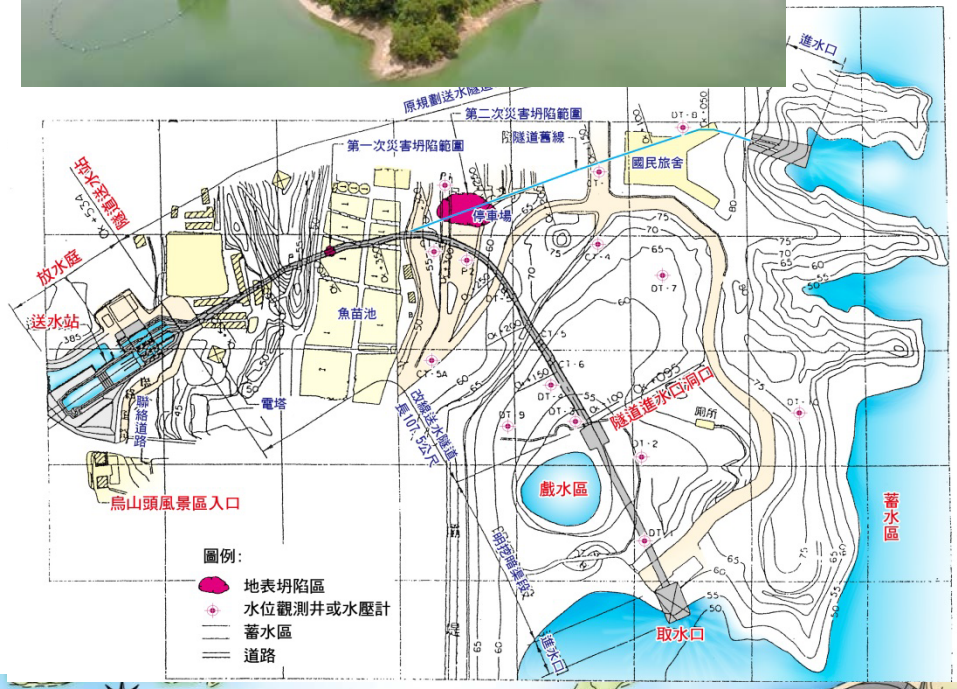
Item	Content		
Type	Overflow chute spillway, Arc-shape inlet		
Intake width	124m	Outlet width	18m
Length	636m	Height of side wall	4.45m
Overflow Elevation	EL.58.18m	Design Flow	1,500cms

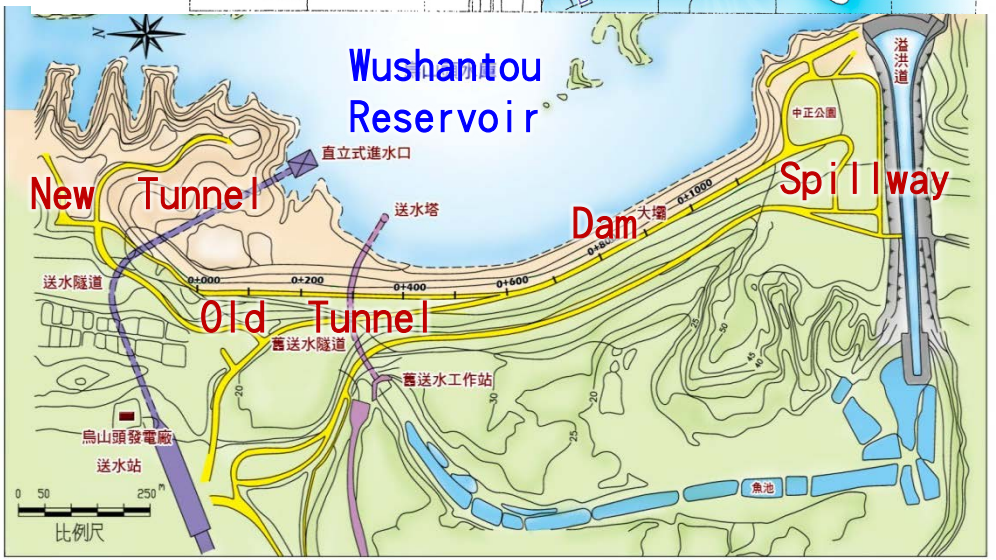
Current Situation



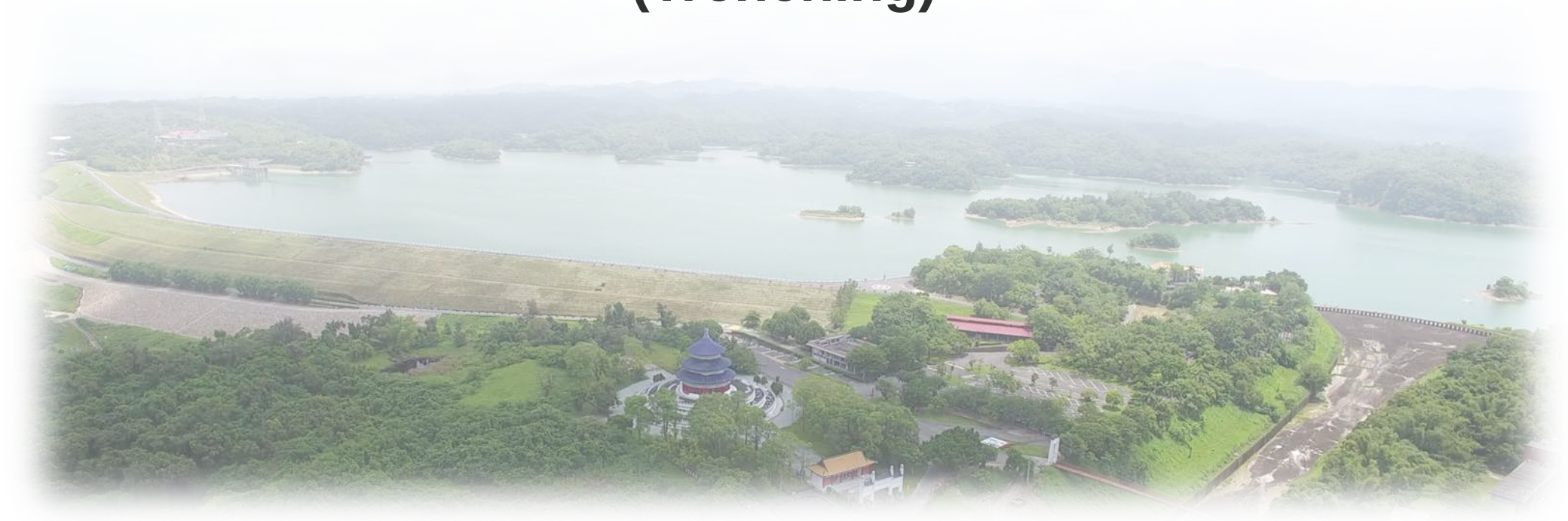
Diversion Tunnel

Item		Content
Old Diversion Tunnel	Intake tower	RC structure, height 14.85m, ϕ = 8.48m。
	Diversion tunnel	horseshoe-shaped tunnel, length 154.54m, width 7.58m, height 7.88m。
	Delivery pipe	Two pipe(162.03m、168.93m), ϕ =2,730mm, tube-wall thickness 12.7mm
	Gate valve	butterfly valve(ϕ =2.73m)，intercepting valve*2, needle valve*6, maximum overflow 62cms
New Diversion Tunnel	Vertical Intake	Length 30m, width 25.4m, length 27.5m, intake hole*4 (H*W=4.2m*4m)
	Culvert	ϕ =4.1m, length 158m, inner lining 9mm steel tube
	Diversion tunnel	ϕ =4.1m, length 409.5m, inner lining 9mm steel tube
	Penstock Tunnel	horseshoe-shaped, height 5.7m, width 6.0m, length 32m Penstock ϕ =4.1m, length 32m
	Delivery Station	length 24m, width 20m, height 23.8m, semi-underground RC structure. Design flow 90cms, normal flow 68cms





Pre-work of the fault investigation (Trenching)

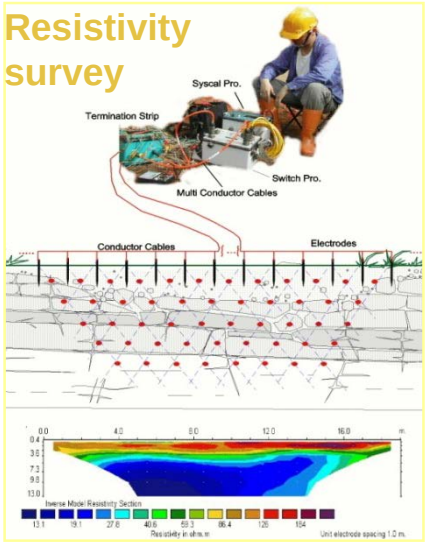


Geological investigation

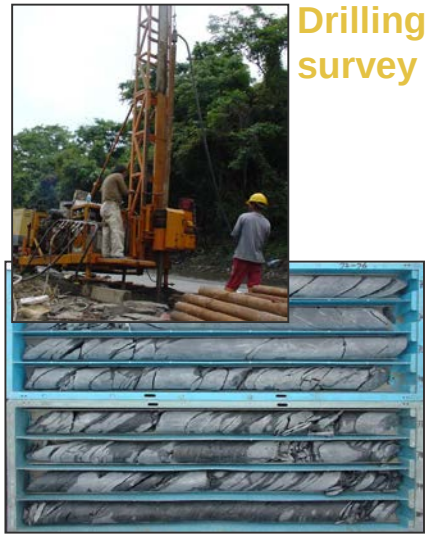
- **Data collection and analysis**—Collecting researches and reports related to Liuchia active fault
- **Morphological analysis** —Via LiDAR scanned DEM to analyze the structures
- **Subsurface geological survey**— Regional stratigraphy, lithology and fault structure characteristics survey related to Liuchia active Fault
- **2D electricity profile survey and borehole drilling**— To reveal the possible fault trace location and the detail fault profile model of the Liuchia active fault
- **Trenching and C14 dating**— To find evidence of paleo-earthquakes; Slip rate of the Liuchia fault via stratigraphy throw and C14 dating results

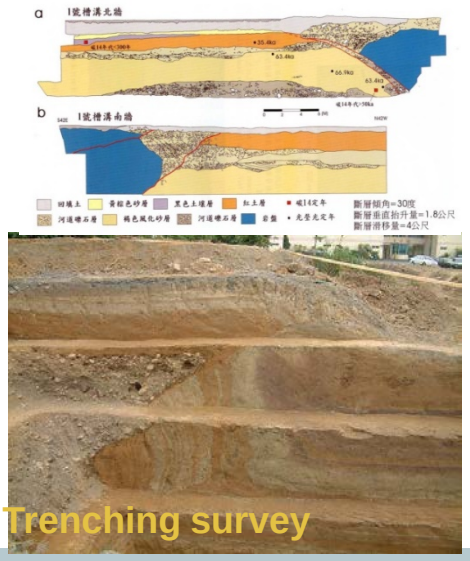
Geological field survey

Resistivity survey



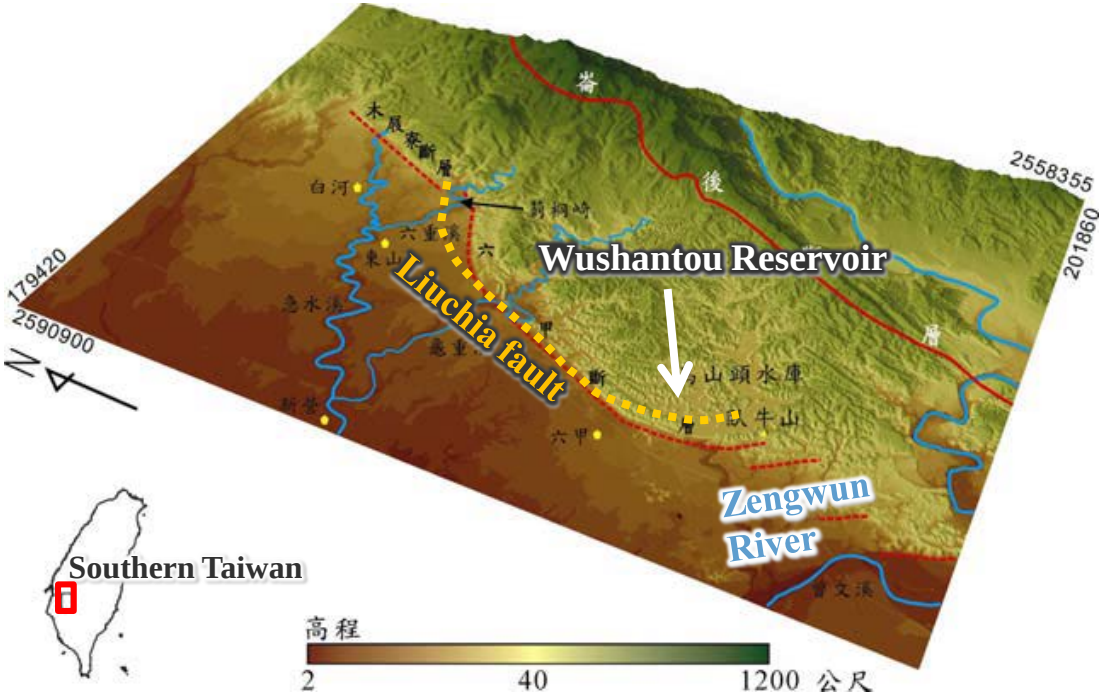
Drilling survey

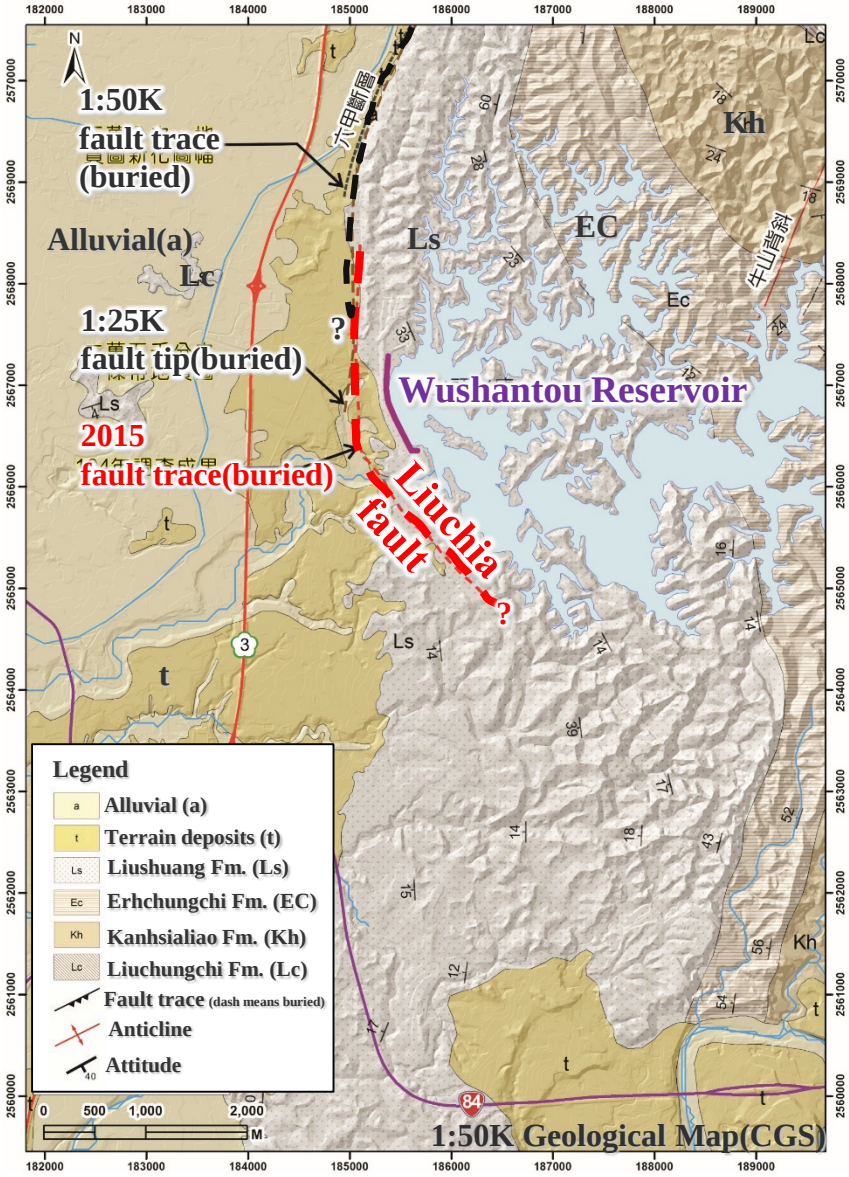




Data collection and analysis

Geological setting



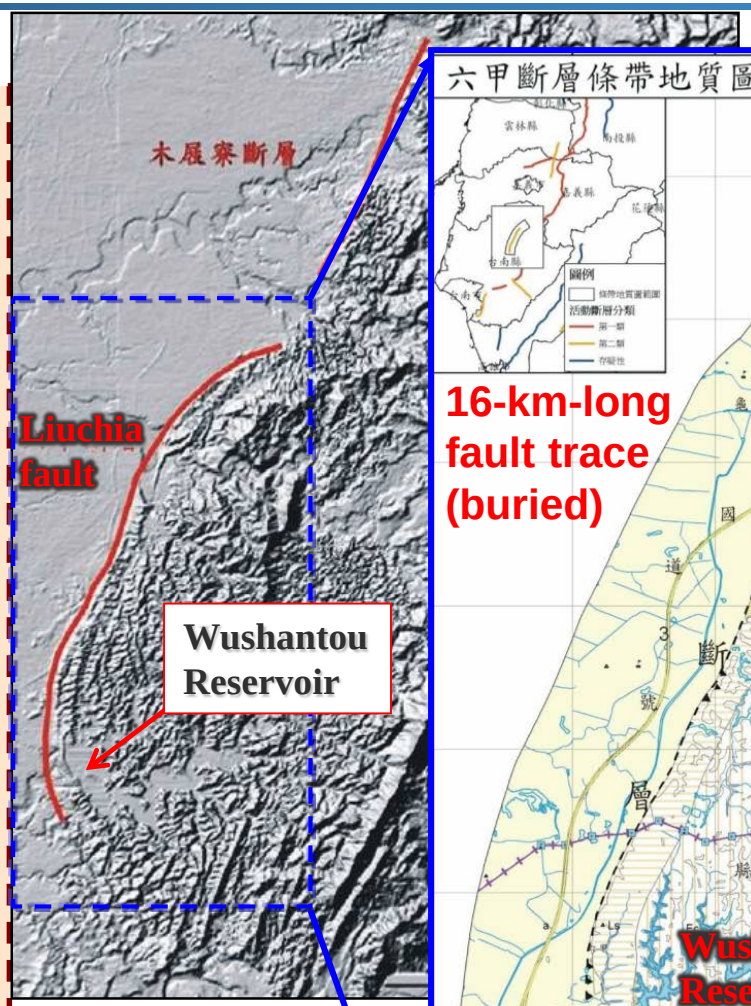


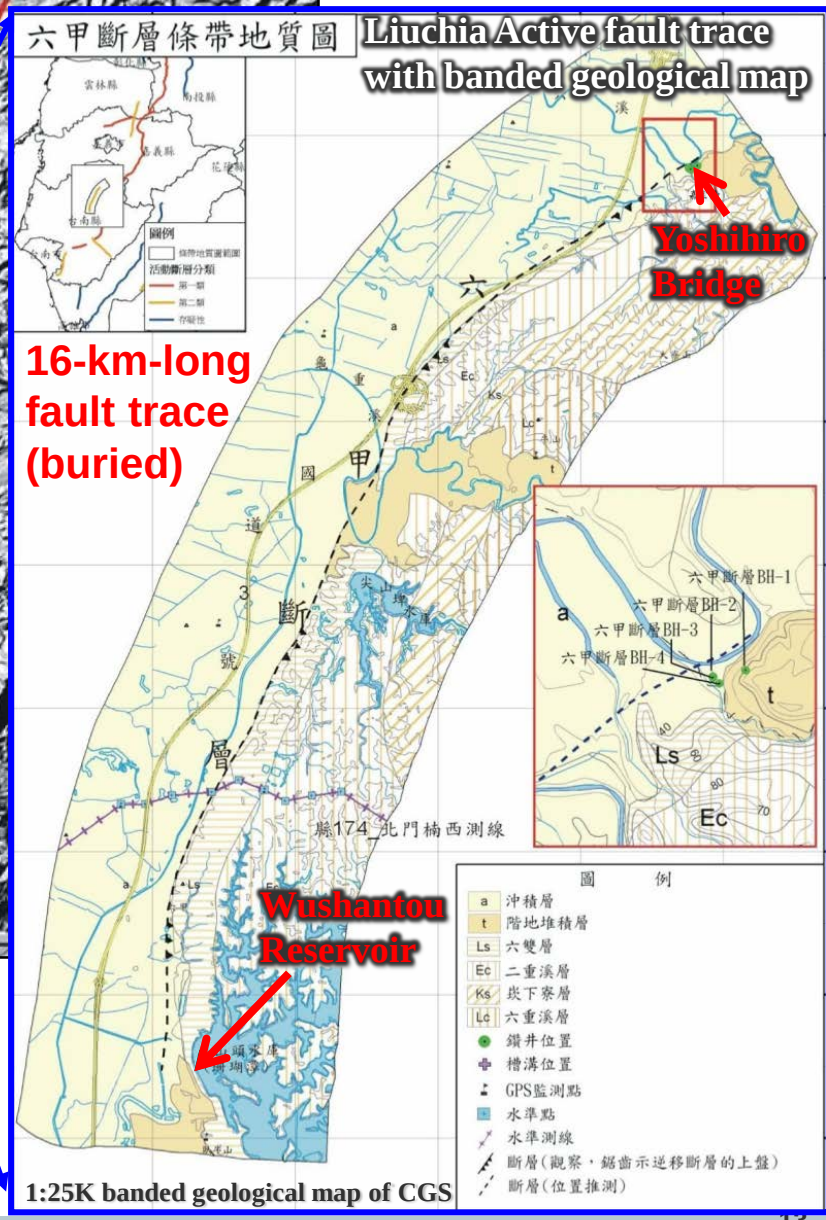
- Wushantou Reservoir located in the **western foothill boundary in south western Taiwan.**
- A rising terrain with a distinct lineation along the eastern side of the Liuchia fault, which can trace to **Wushantou Reservoir**.
- **Muddy sandstone and Mudstone** strata formed from Holocene to Pleistocene exposure near subsurface.

Data collection and analysis

The Liuchia Active fault (1/2)

- Shih et al.(1986)(**石再添等**) found that there's an obvious arc lineation escarpment situated on the west of the Chiayi hill.
- Tilted terrain covered by the Holocene strata nearing the west side of Chiayi hill suggest that the Liuchia fault exist (Shih et al., 1986).
- Chiang et al.(1998)(**張徽正等**) present that the fault trace of Liuchia fault start from the north Yoshihiro Bridge (Liuchungchi) to the south Wushantou Reservoir with **total distance 17km.**
- CGS (Lin et al., 2012) posted that **the fault trace is about 16-km-long**, with active evidences of 11,700 BP, showing the Liuchia faul is an active fault which can be categories into the first category active fault of CGS, Taiwan, MOEA .





Data collection and analysis

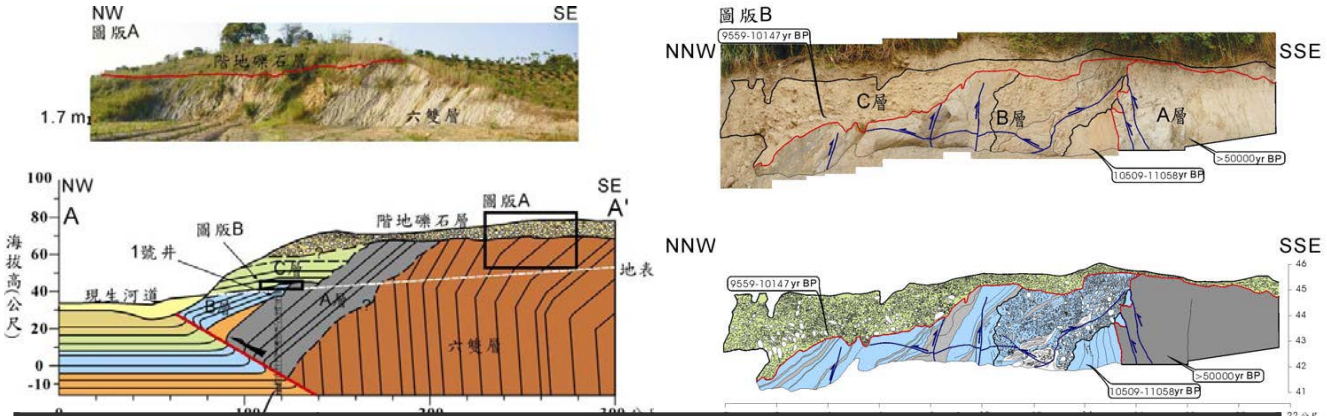
The Liuchia Active fault (2/2)

- **Location of the fault and the fault trace distance:**
  - From the north Yoshihiro Bridge (Liuchungchi) to the south Wushantou Reservoir.
  - Buried fault trace is about 16-km-long (CGS).
- **Topography and subsurface geological setting:**
  - Flexure rock formation (Pleistocene) exposed on the hanging wall of Liuchia fault. (NS to N20° W, dipping 60 ° W)
  - Holocene stara exposed on the western side of the fault. (Dipping less than 20 ° W)
- **Under ground geological structure characteristics:**
  - **Liuchia fault is an oblique reversed fault with left-lateral movement.**
  - The fault plane attitude is about N40°E/30°E in the north, but change into 30°E in the south part.
  - The deformation cause by the faulting decrease in the south part of the fault near the Wushantou Reservoir.
  - The flexure rock formation still exist on the southern part of hanging wall of the fault with dipping angle around 30 ° toward east.

Data collection and analysis

The Liuchia Active fault outcrops(1/2)

- Yeh et al. (2005)(**楊志成等**)found a 300-meter-long outcrop near the south bank of Liuchungchi. (Kiritizaki (**荊桐崎**))
- The Kiritizaki profile shows that the Liushuang Fm. is tilting to west, which covered by Holocene strata.



Terrace deposits (gravel)	Horizontal gravel layer cover on layer C	-
Layer C	Include sand and gravel with small piece of charcoal and shell	B.P. 9,853±294
Layer B	Sand and mud interbed cover on sand and gravel layer；Charcoal, mud and marine phase fossils can be found in the cross bedding	B.P. 10,784±275
Layer A	Blocky mud stone with sandstone	>B.P. 50,000
Liushuang Fm.	1m thickness Ss and Ss/Sh	-

Data collection and analysis

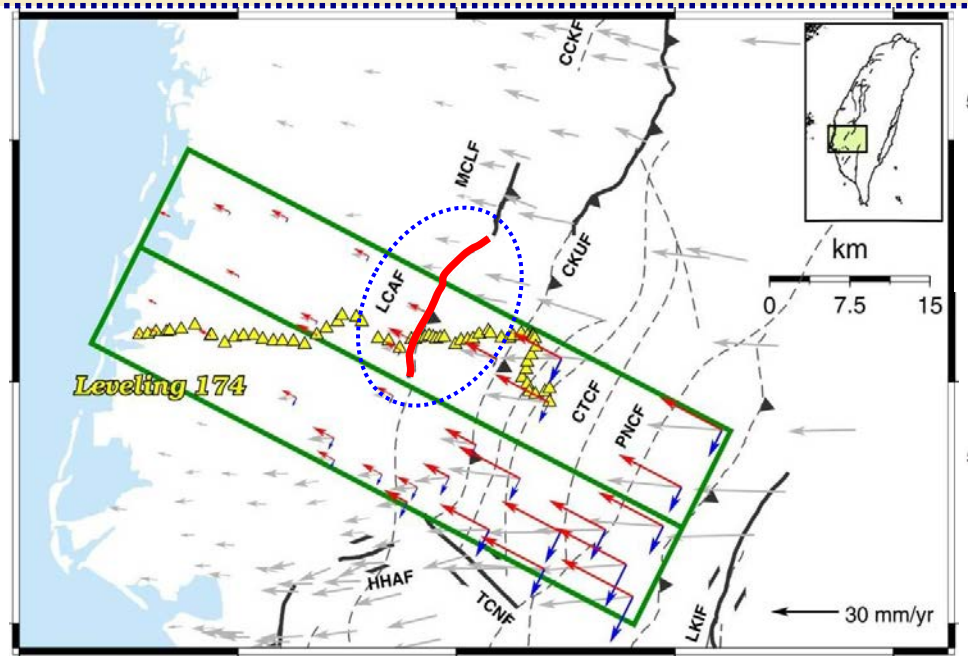
The Liuchia Active fault outcrops(2/2)

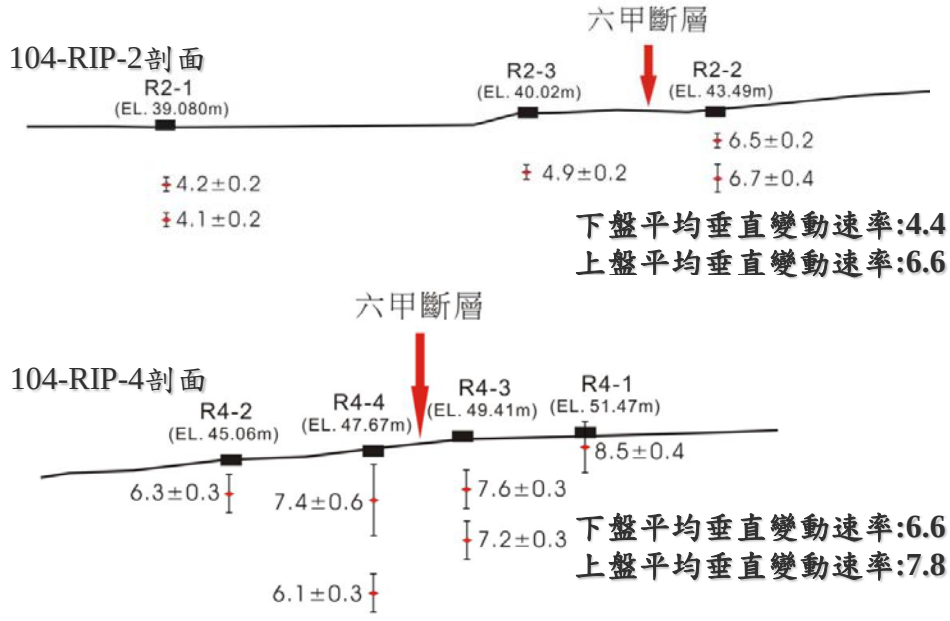
- Lin et al.(2000) found a outcrop represented the Liuchia fault thrusting on the western side of National Tainan University of the Arts.
- Drag fold found on the hanging wall that the fault plane dips to N-E direction.
- The strata can be defined as Liushuang Fm. on both hanging wall and footwall of the fault.
- The structure could be one of the branch fault or representing a rupture near the anticline structure.
- Base on the geological investigation results, the evidence of the fault thrusting is not obvious at all.

Data collection and analysis

- Fault activity (mobility)：
  - Young et al.(2005) – Vertical uplift rate **5.5 mm/yr**；Horizontal slip rate **11 mm/yr**
  - Chen et al.(2006) - Vertical uplift rate **6.33±0.06 mm/yr**， Horizontal slip rate **12.7 mm/yr** (30° fault plane)
  - Chianan Irrigation Agency(2015) – At the Wushantou R. vertical uplift rate **1.2~2.2mm/yr**；Long term horizontal slip rate **1.4~2.8 mm/yr** (60° fault plane)

➔**The southern part of Liuchia fault has higher fault plane angle, less slip rate than the northern part of the fault**



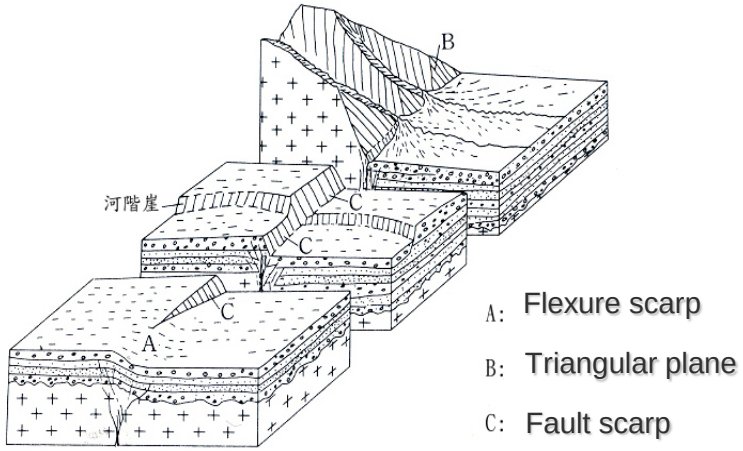


Morphological analysis and Geological survey

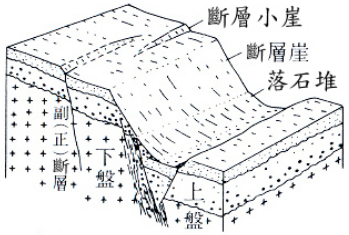
❖ Geomorphology of Fault

- Via 1m LiDAR DEM

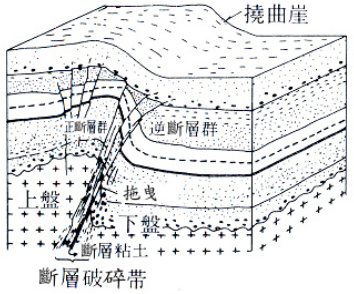
Topography characteristics of faulting



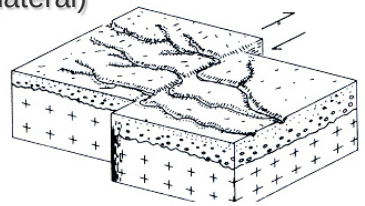
Normal fault



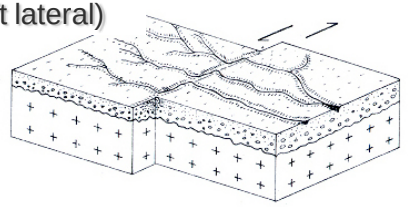
Reverse fault



Strike slip fault (right lateral)

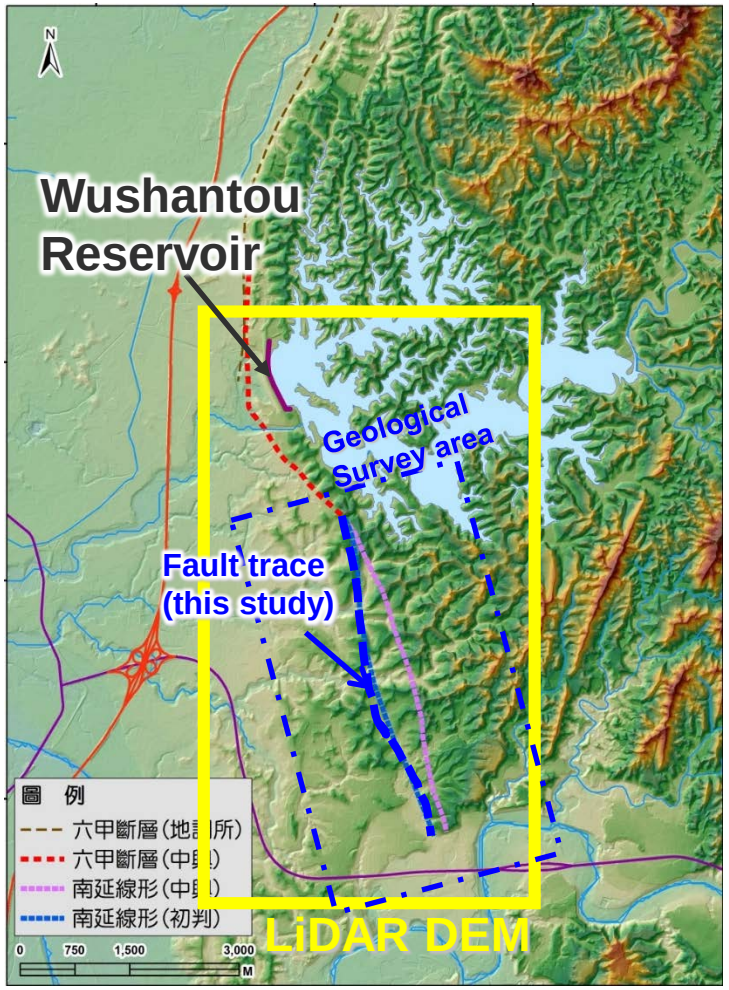


Strike slip fault (left lateral)



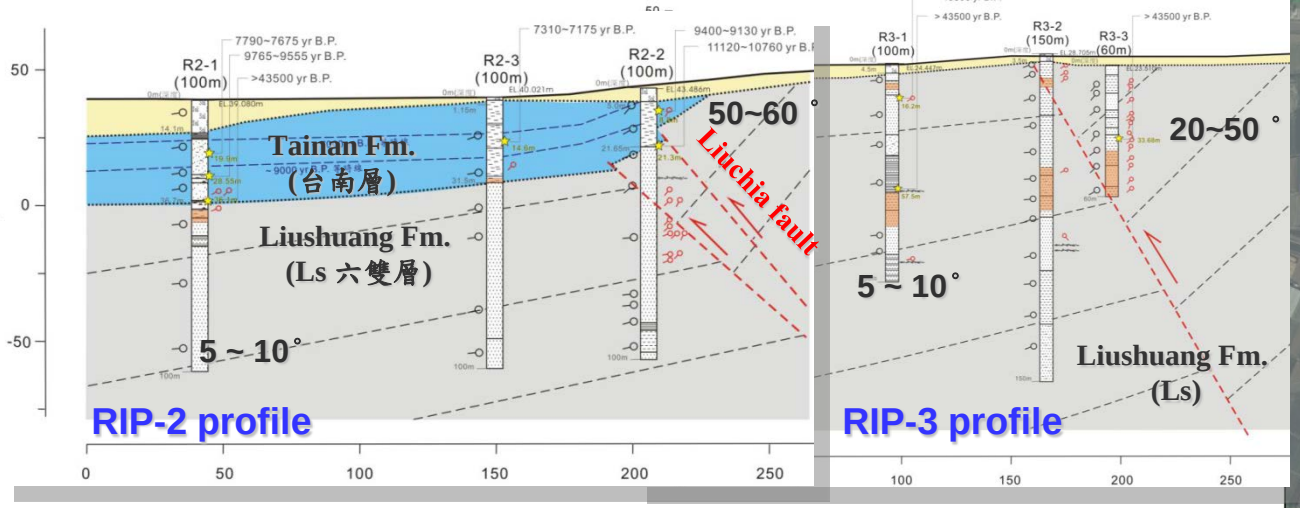
❖ Surface geological survey

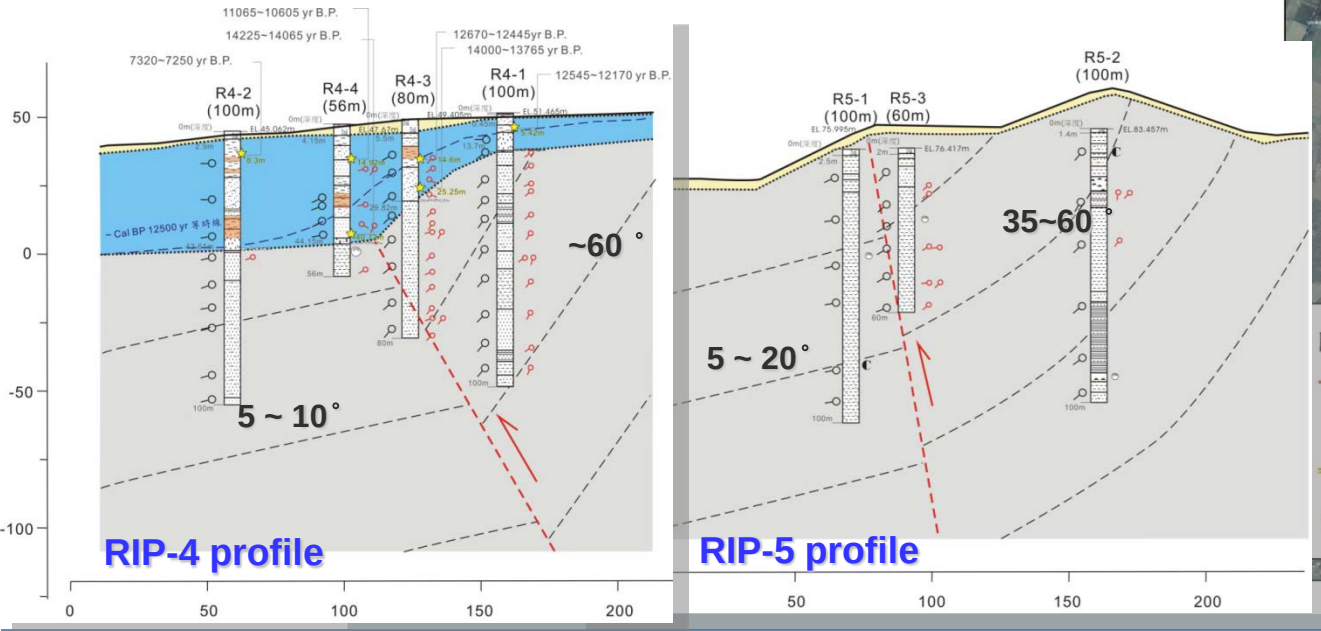
- Detail investigation focusing on the near by area of Wushantou Reservoir

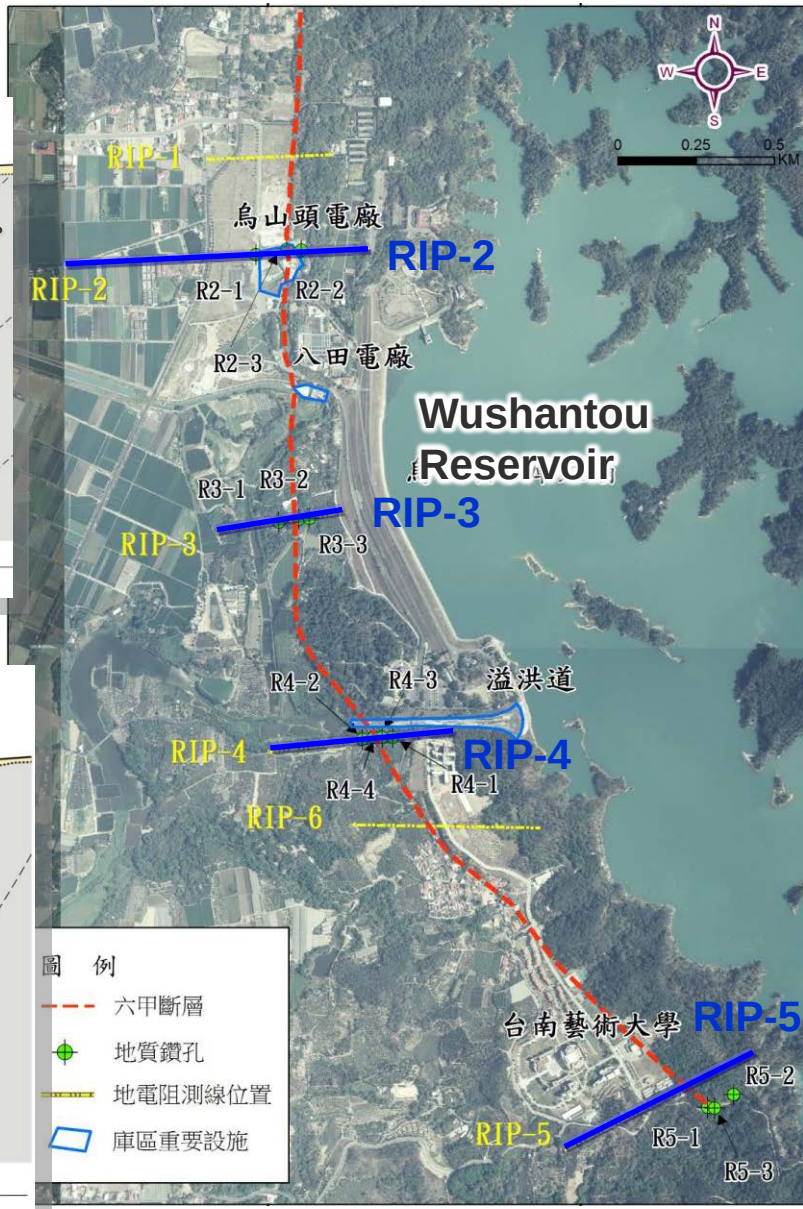


Data collection and analysis

RIP survey and drillings at Wushantou Reservoir



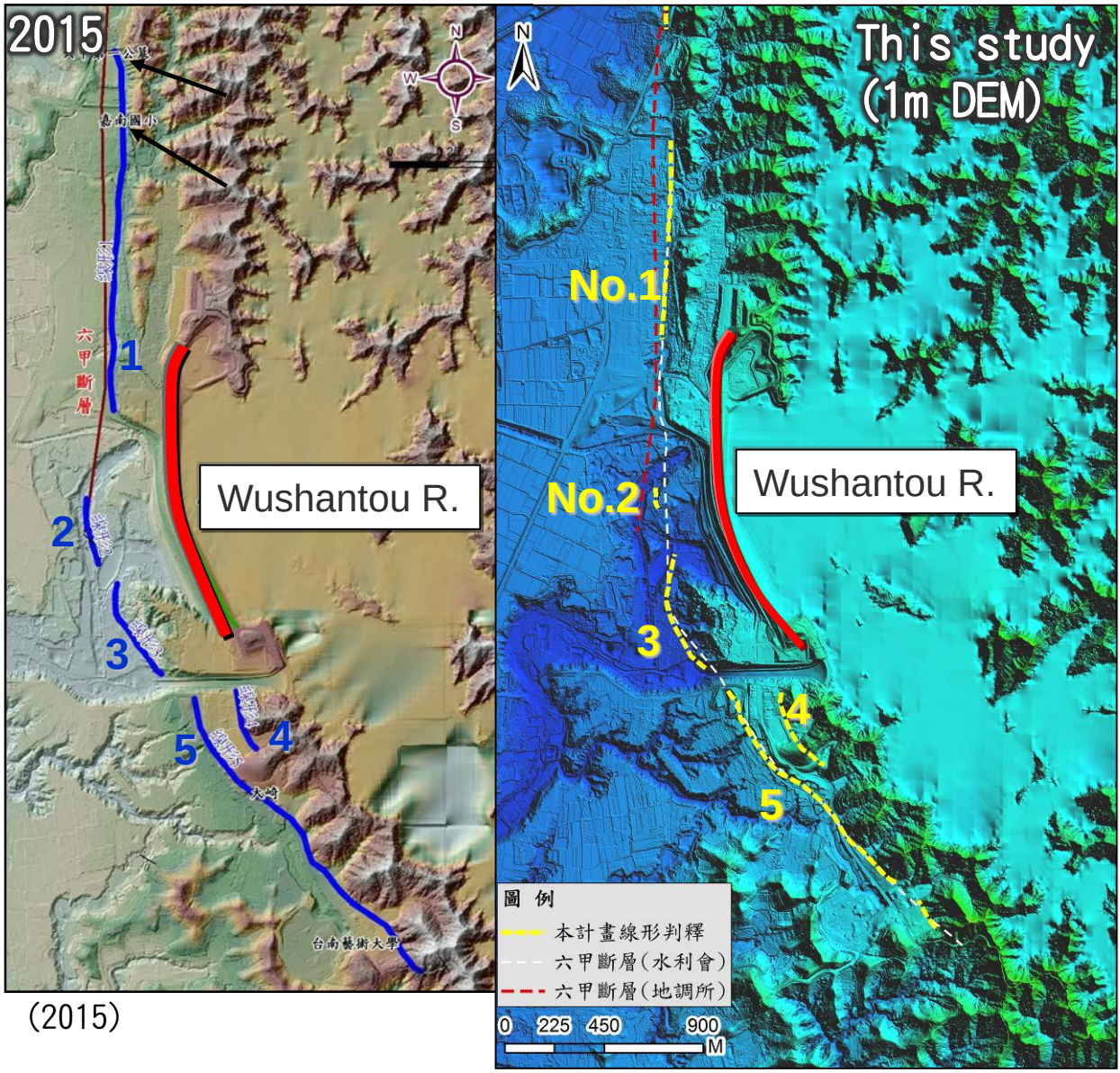




前期計畫(2015)地質探查成果

Morphological analysis and Geological survey

- Possible lineation of the fault scarp can be found near the Wushantou Reservoir.
- Those lineation are N-S direction with an arc shape.
- The topography lineation No.1 and No.2 located the fault trace that the CGS defined.
- The results show that the possible fault scarp lineation located in the west of Wushantou Reservoir.



(2015)

Surface geological survey

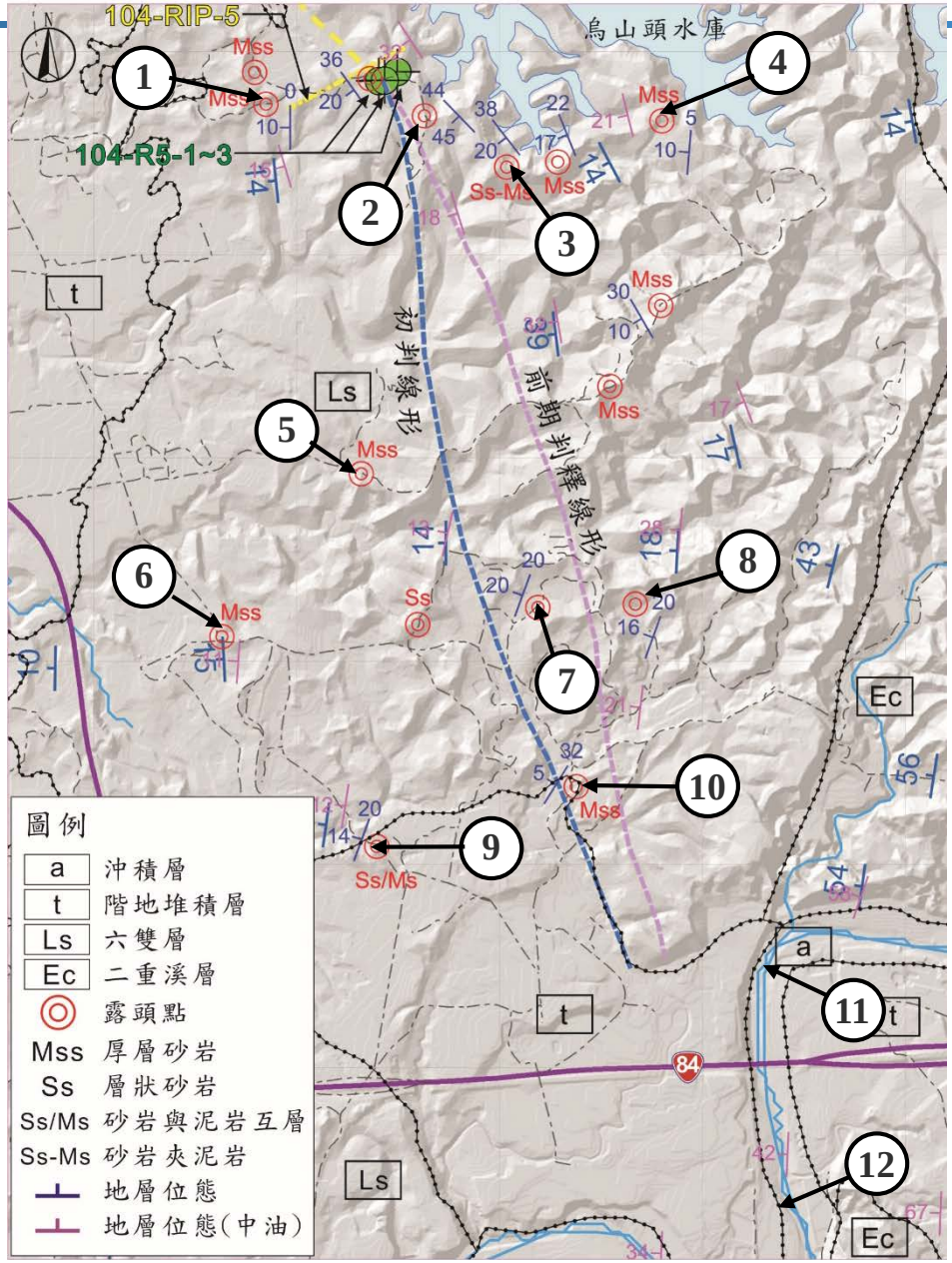
- The Pleistocene Liushuang Fm. expose in the subsurface with muddy sandstone.
- The attitude of the rock Fm is NE in north, but change into NS~NE dipping to west 5~20° .

Thick Sandstone layer dipping 10° to west

Shattered Sandstone and mudstone interlayer dipping 45° to west

Sandstone and thin mudstone interlayer dipping 20° to west to west

Thick sandstone layer dipping 10° to west



Surface geological survey

Thick sandstone with out shatterd

Thick sandstone layer dipping 15° to west

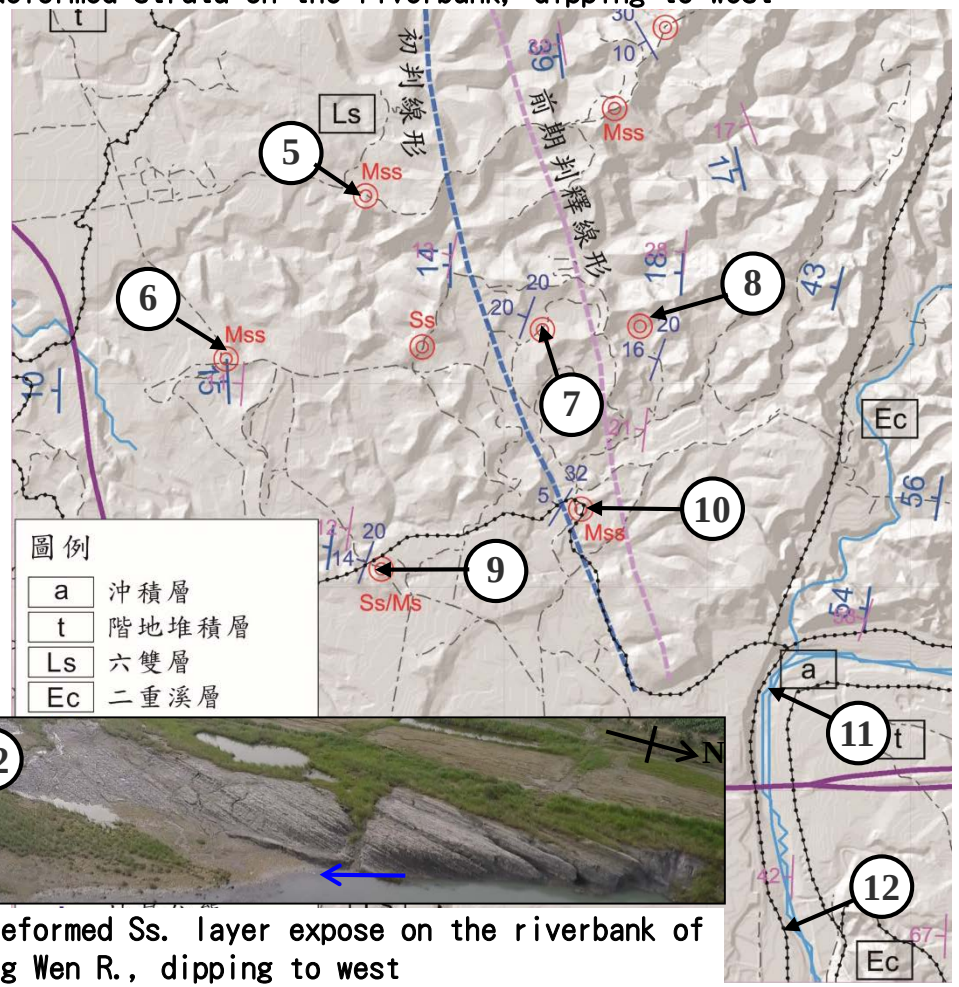
Undeformed strata on the riverbank, dipping to west

Stratiform sandstone dipping 20 to west

Stratiform sandstone dipping 16to west

Ss and Mds interlayer

Thick Ss dipping 5 to west



Undeformed Ss. layer expose on the riverbank of Zeng Wen R., dipping to west

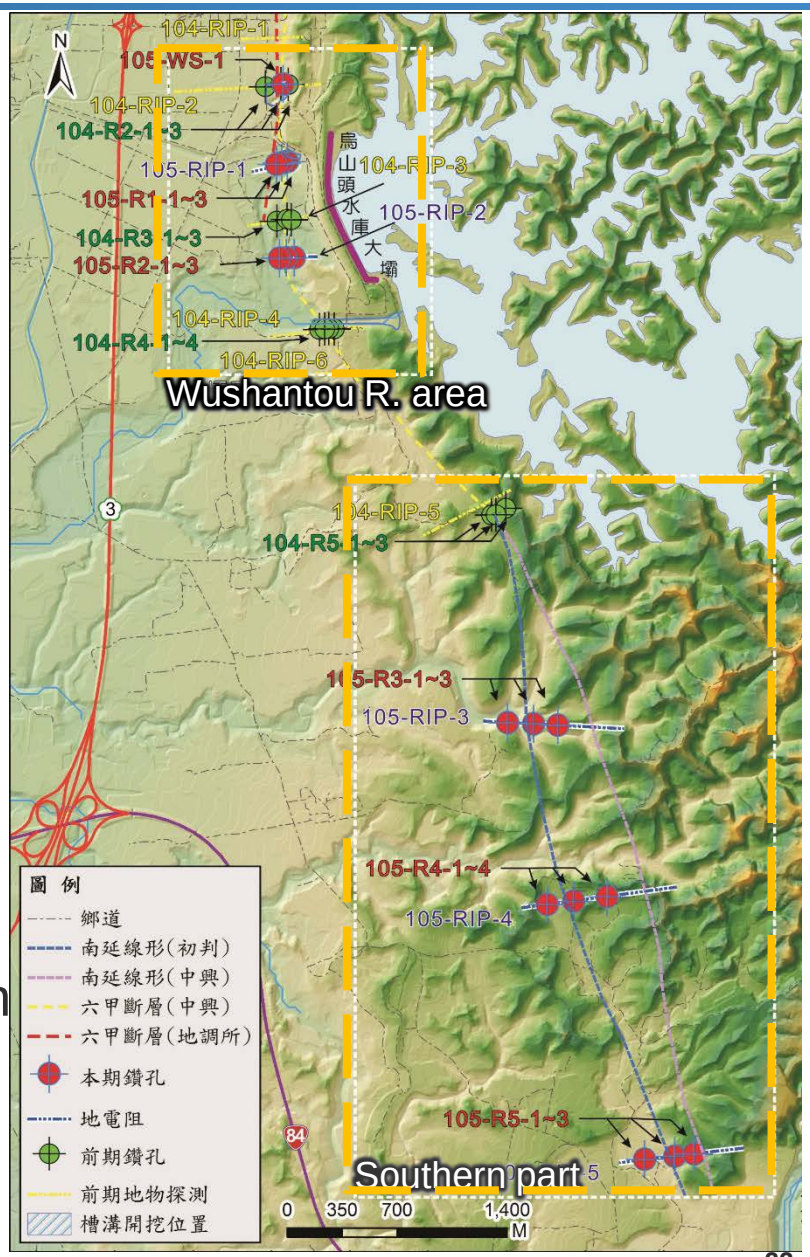
Geophysical survey and Drilling

Geophysical survey

- **Purpose:** Investigate the distribution of the geological structure on subsurface near the Wushantou R.
- How to? Set the RIP survey line perpendicular to the possible fault scarp lineation
- **4 RIP survey lines** and 1 reflection seismic line, totally 3,400-meter-long.

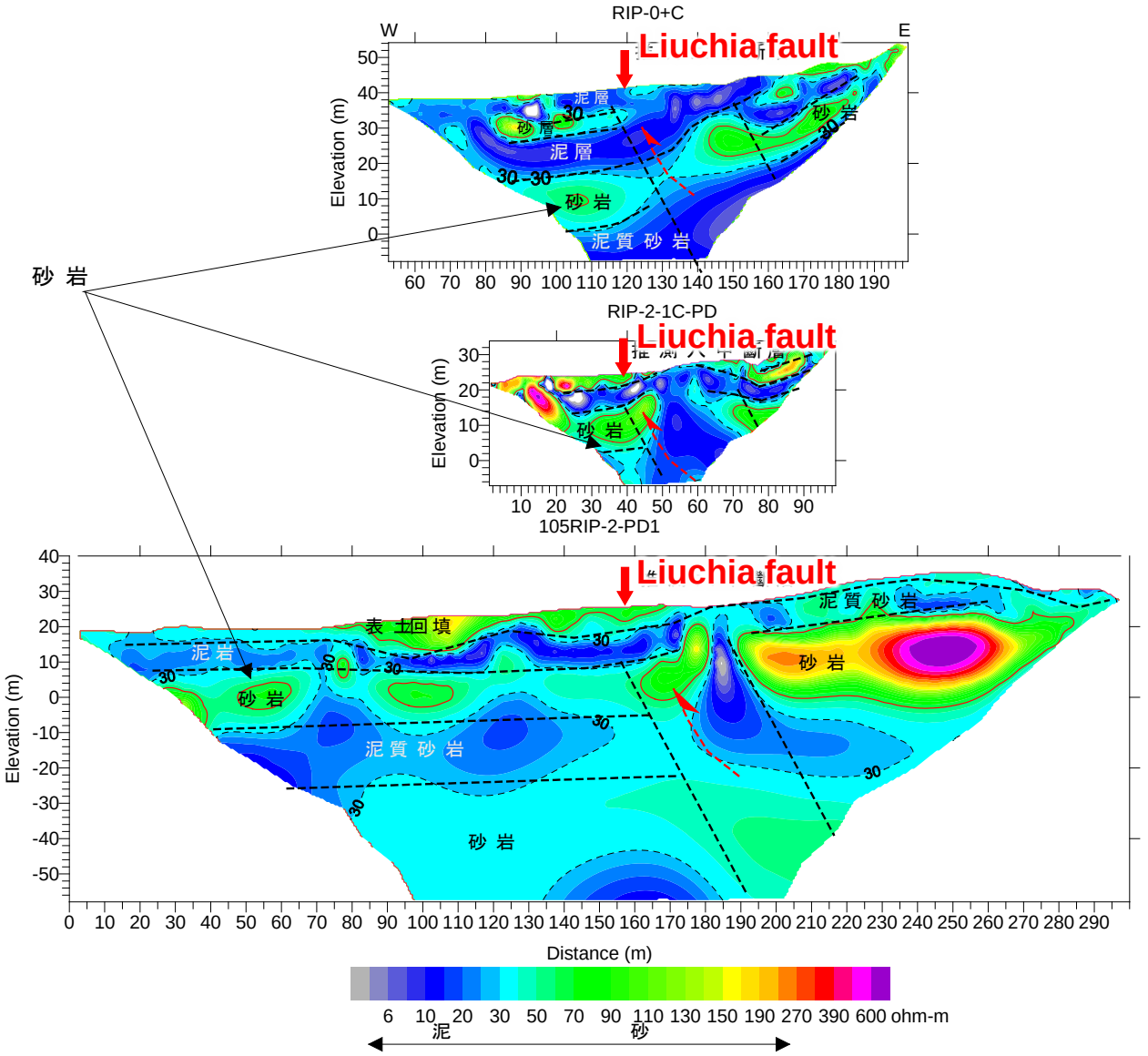
Drilling

- **Purpose:** Investigate the southern extension of the Liuchia fault.
- **How to?** Base on the Geophysical survey results perpendicular of the possible fault trace.
- **7** boreholes near the Wushantou R., and southern part **10** boreholes.
- **1,050-meter-long** drilling logging data are documented



Geophysical survey

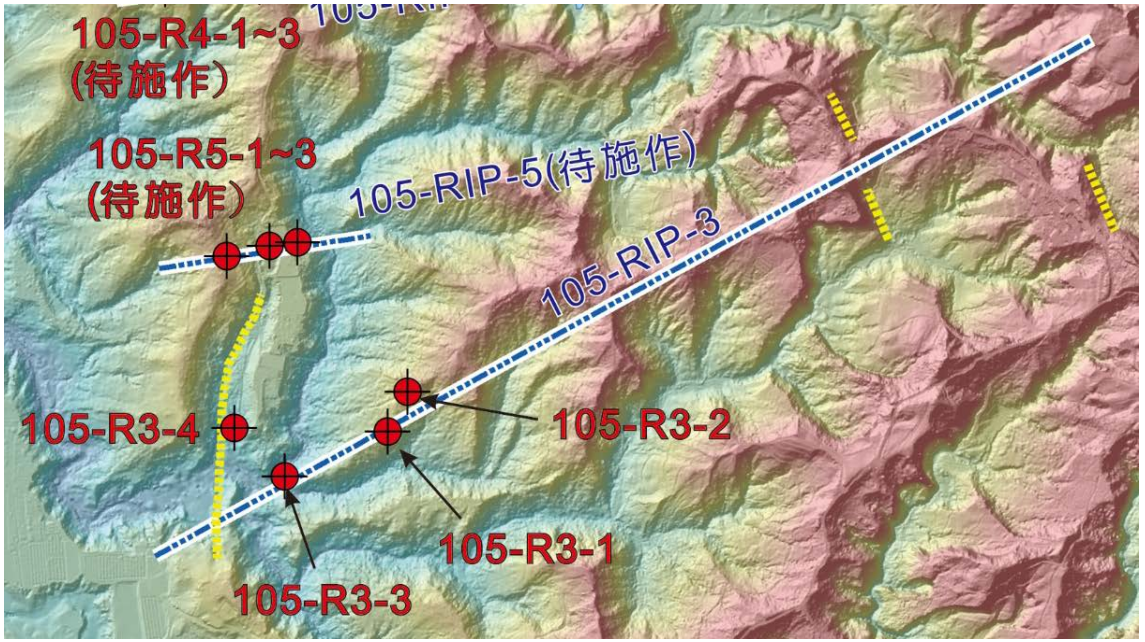
❖Structure distribution of the Liuchia active fault traces

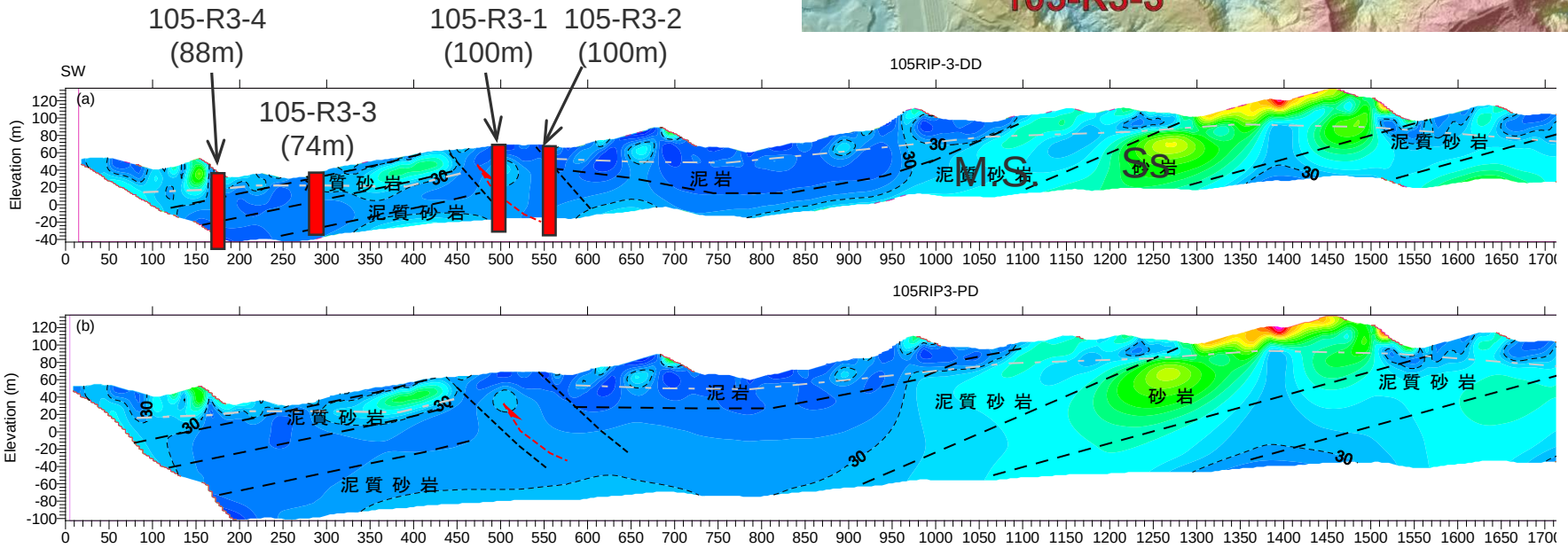


Geophysical Survey

South part 105-RIP-3

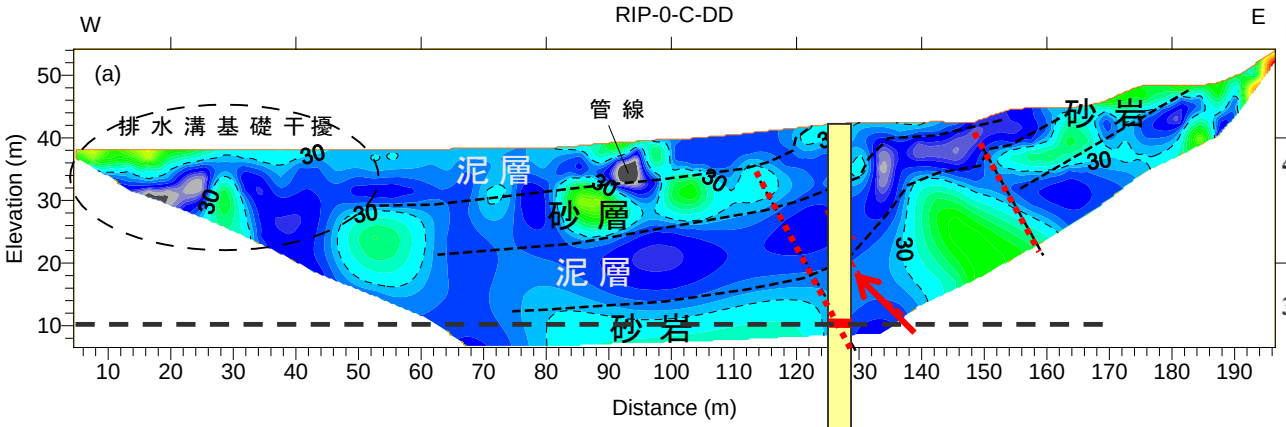
- ✓ The survey line length is about 450~550 m.
- ✓ Resistivity unconformities region dipping to NE direction.
- ✓ It suggests that the characteristics are matched to the distribution of the Dam area

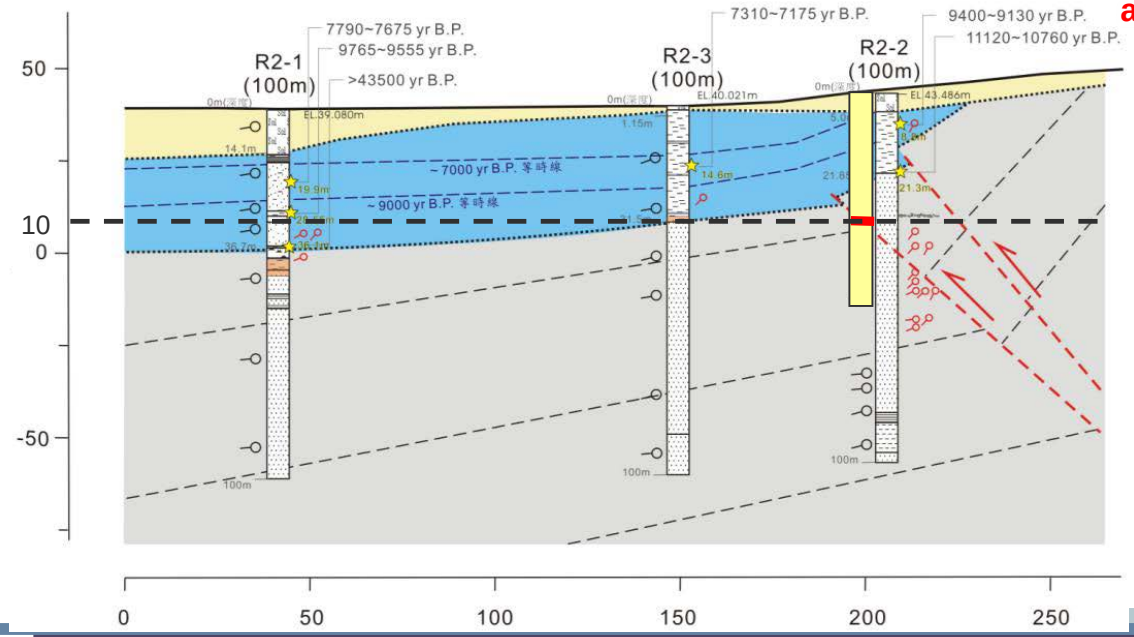


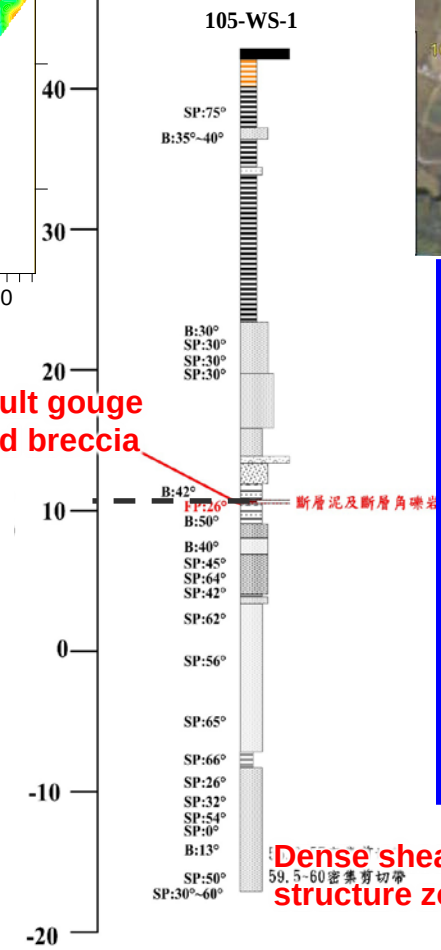


Drilling

❖The Wushantou power plant area 105-WS-1(60m)



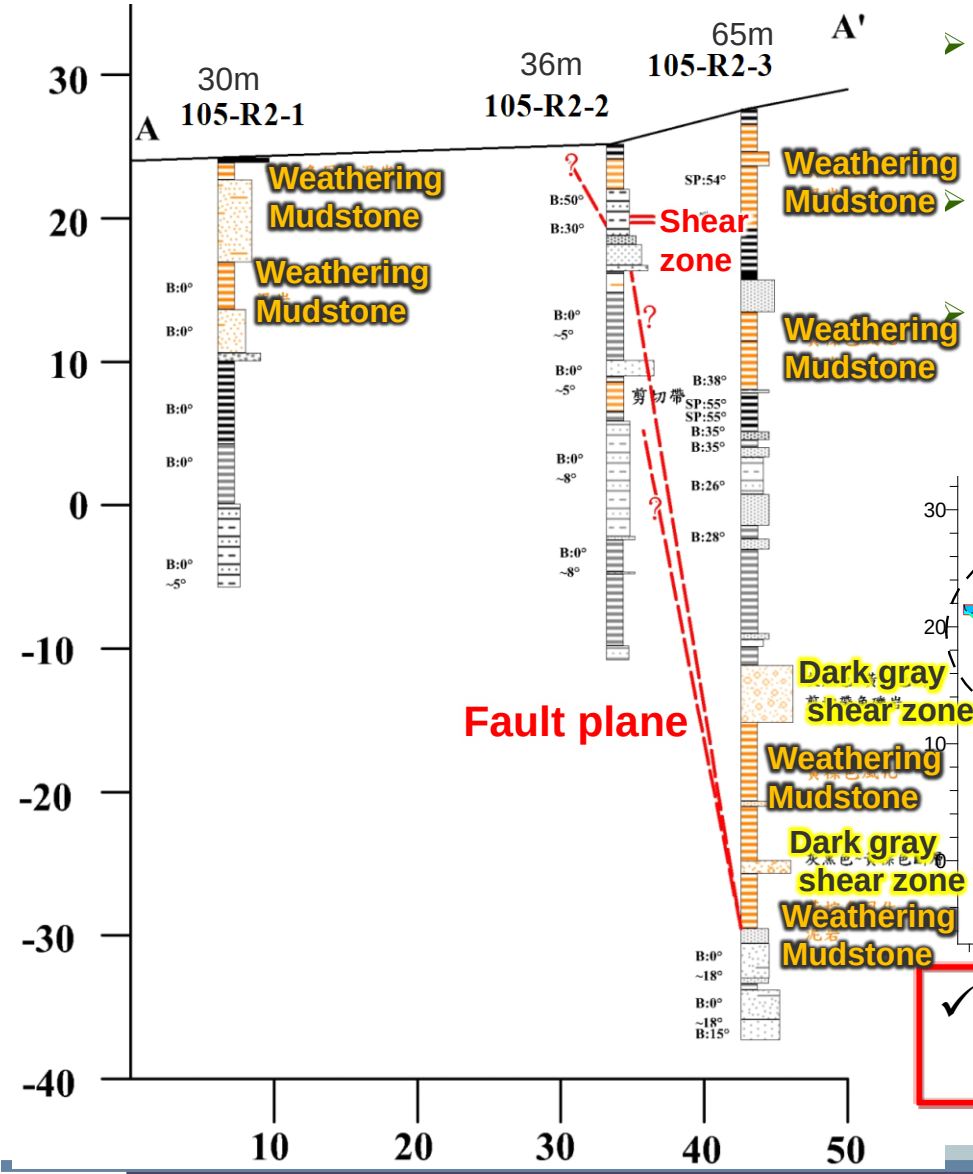




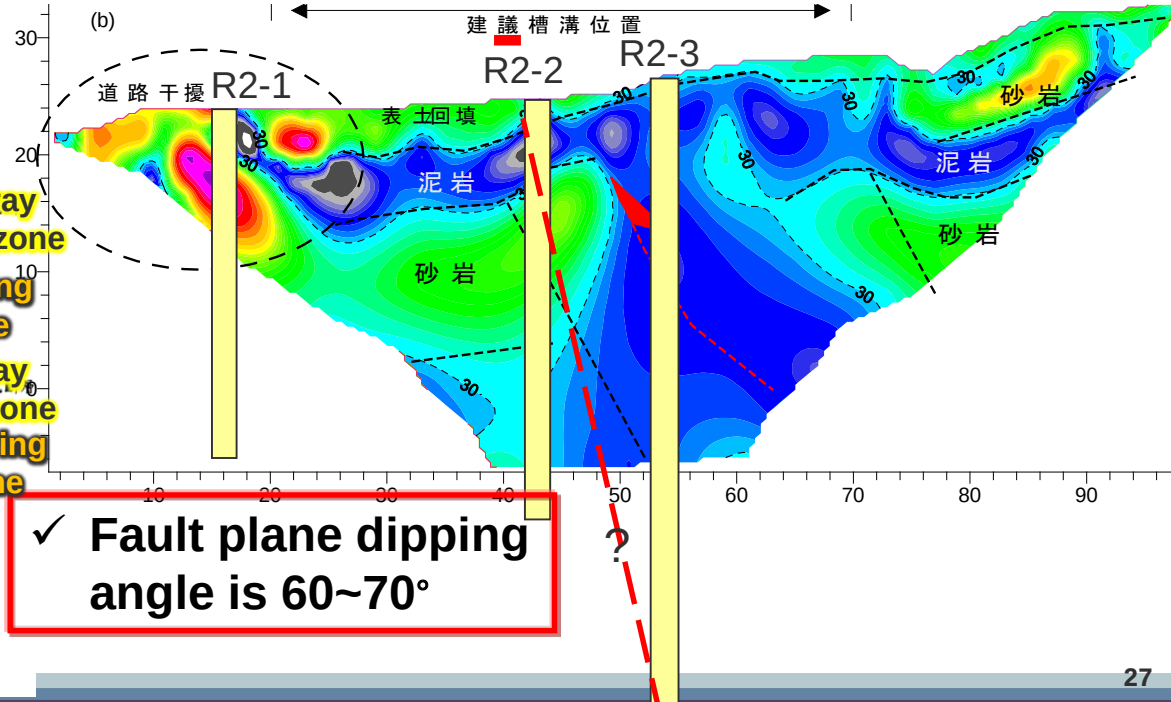
- Dense shear structures in all depth with 26˚~75˚dipping plane
- At depth 32.06~32.45m fine fault gouge and breccia. (apparent dip is 26˚)

Drilling

❖Down stream of the Dam 105-R2-1~3



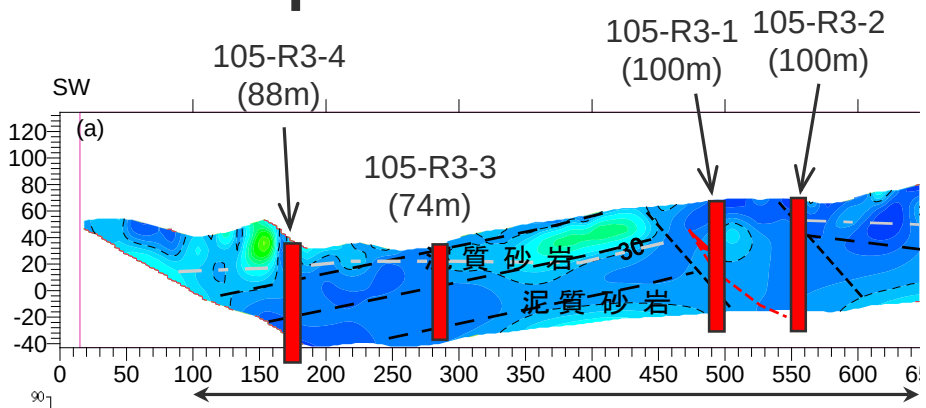
- R2-1: Sandstone and mudstone interlayer. Near flat bedding plane on footwall.
- R2-2: 0~6.4m bedding dips 30~50 ˚5.0~5.4 shear structure. It suggest 0~6.4m is on the hanging wall.
- R2-3: Dense shear structure in 0~57.15m with angle 26~38 ˚. (Hanging wall)
- (R2-3)At 38.8~42.78m and 52.46~53.32m with fault breccia and fault shear zone. The shear plane dips around 0˚~18˚. It might be at the footwall of the fault.

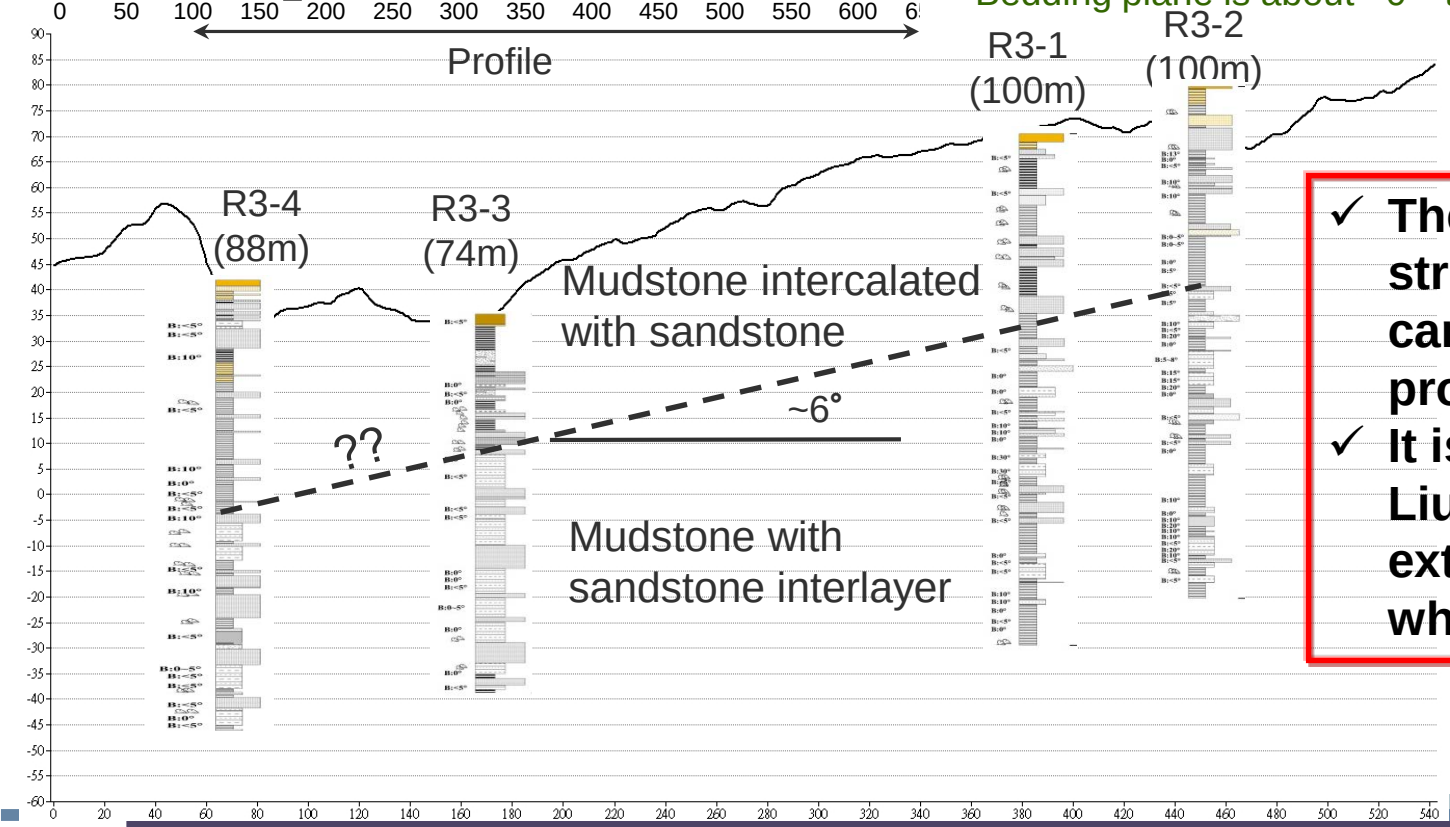


✓ **Fault plane dipping angle is 60~70°**

Drilling

❖South part 105-R3-1~4



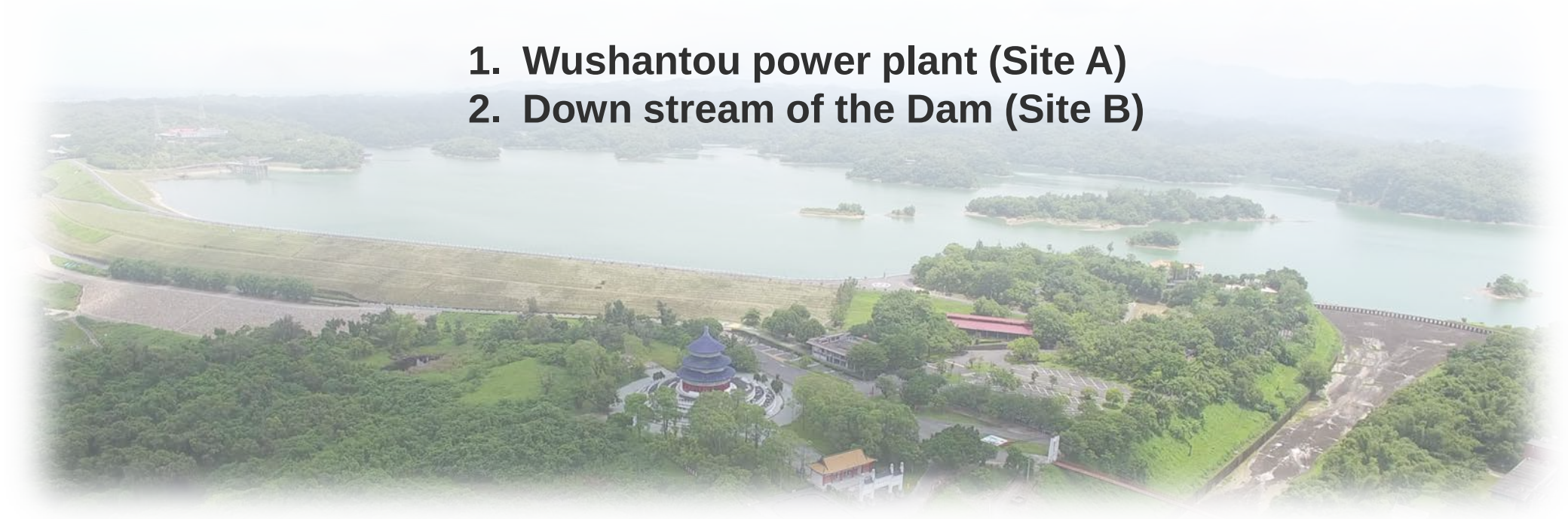


- **R3-1:** Sandstone and mudstone interlayer with debris shell. At the depth of 62-66m, the bedding plane dips to south west 30°
- **R3-2:** Sandstone and mudstone interlayer with debris shell. At the depth of 55m and 85m, the bedding plane dips to south west at 20°
- **R3-3:** Sandstone and mudstone interlayer with debris shell. Bedding plane is about ~0°
- **R3-4:** Sandstone and mudstone interlayer with debris shell. Bedding plane is about ~0° to 10°

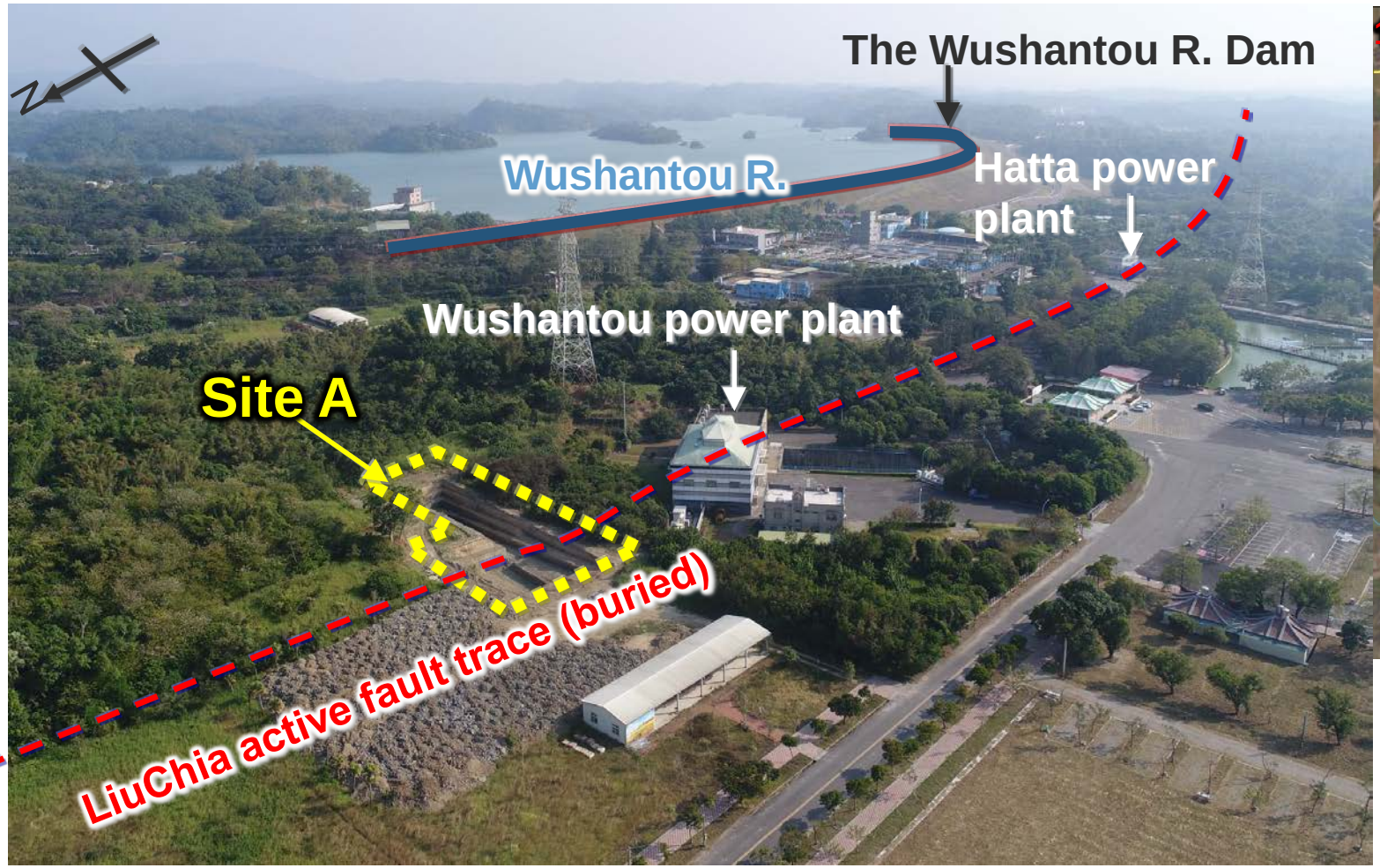
- ✓ **There are no shear structures and flexure rock can be found along the profile RIP-3.**
- ✓ **It is suggested that the Liuchia fault trace didn't extend to the southern part where we investigated.**

Let’s Go Trenching!!

1. Wushantou power plant (Site A)
2. Down stream of the Dam (Site B)



Trenching Site A – At Wushantou power plant



LiuChia active fault trace (buried)

Trenching Site A

Digging and sizes

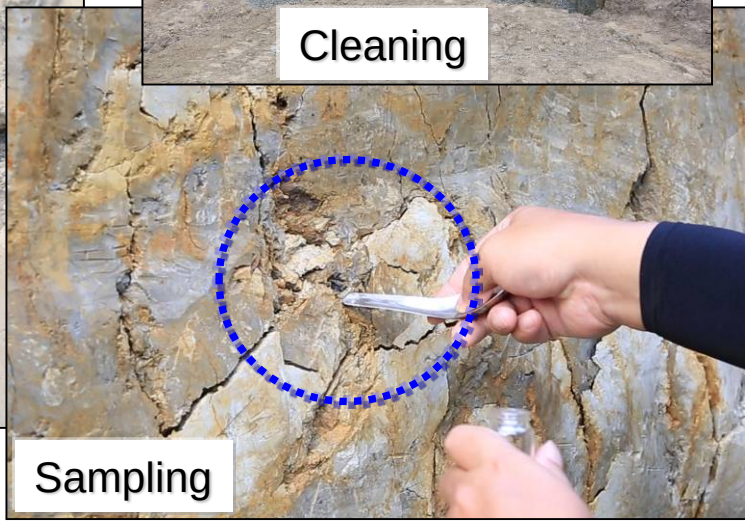
⇨**Each stair of 2-meter-high with 1.5m width.**

⇨**Prof. Lee, C.T.** suggested that expend the trench to east for 10-meter-long. The total length of the trench is 60 meters.

Trenching Site A

Cliff cleaning and sampling

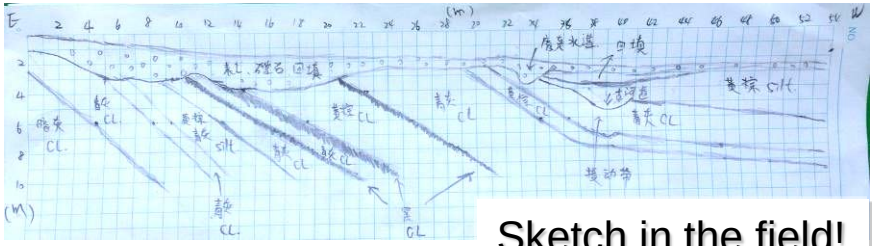
- In order to show the sedimentary structures and shear strucutures
- Finding charcoals and other debris that can be use for C14 dating.
- All the sample were sent to BETA .



Trenching Site A

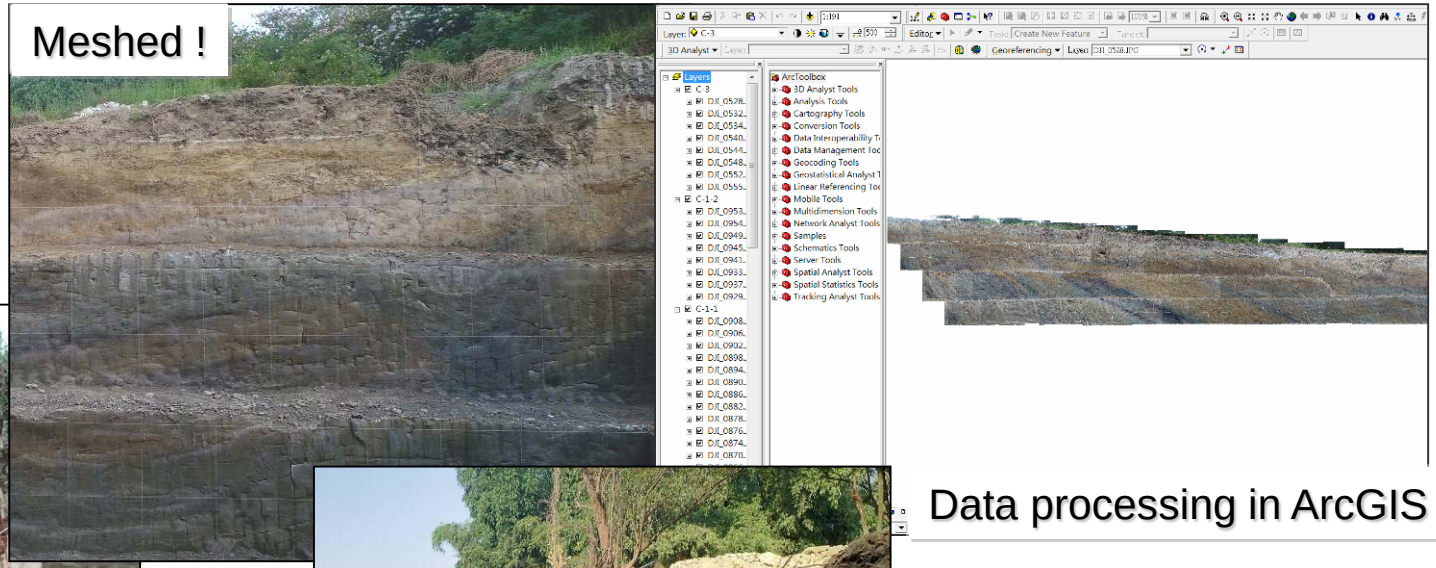
Set mesh lines and documentation

- ⇨The mesh line size is 1x1m for each square.
- ⇨Using high resolution digital camera to document the images.
- ⇨Using ArcGIS to gather the wall images piece by piece together.



Sketch in the field!

Meshed !

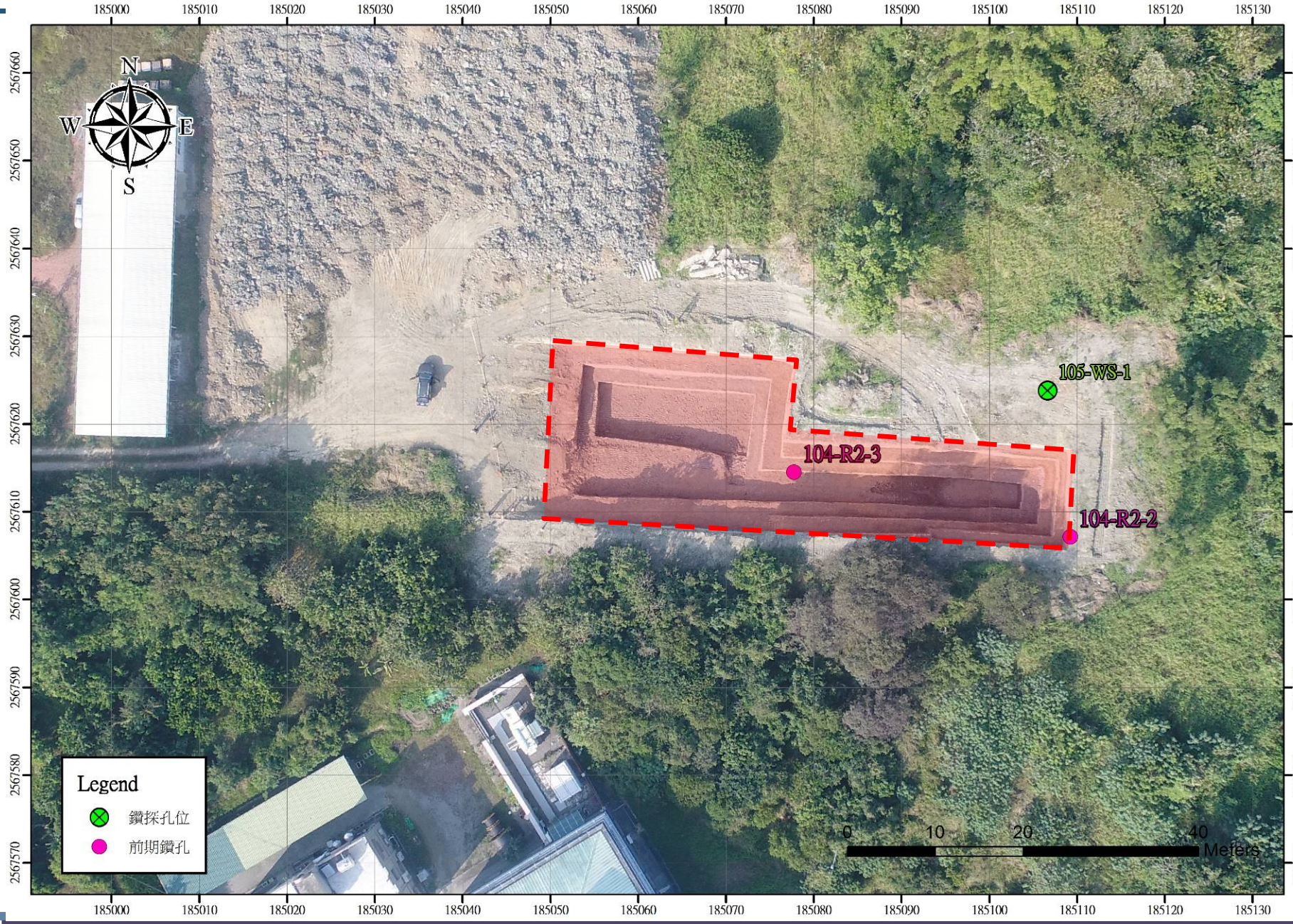


Data processing in ArcGIS

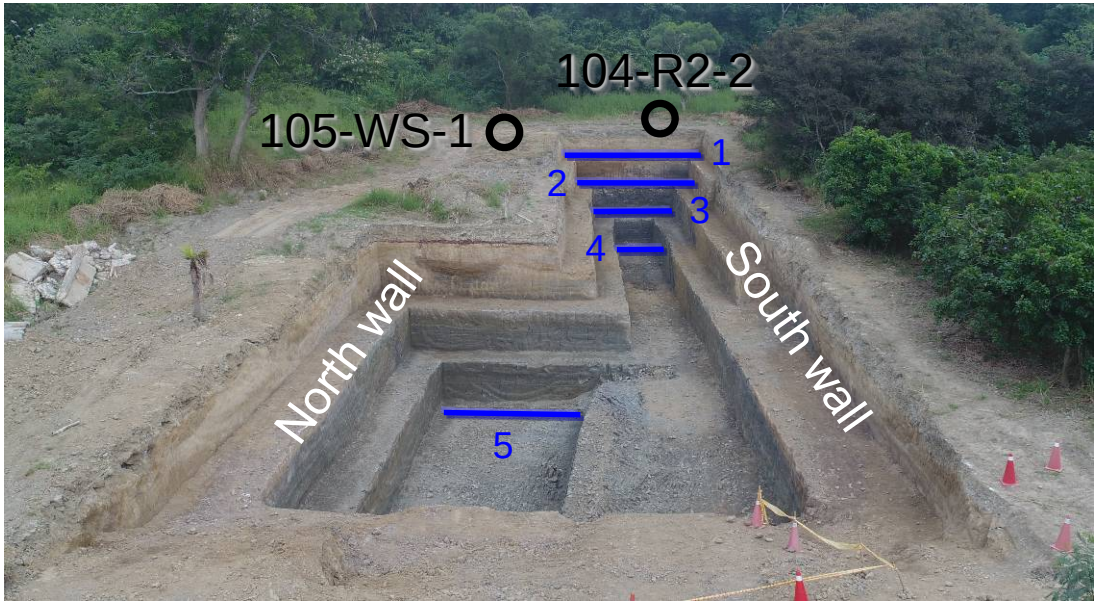
Mesh line setting

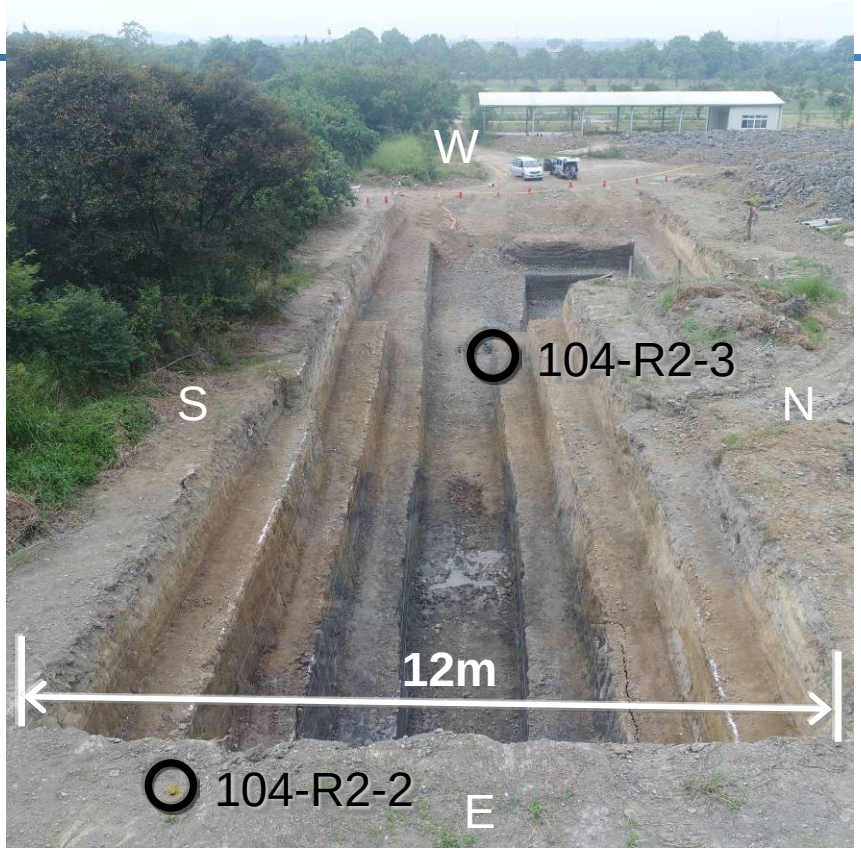
Mesh line setting

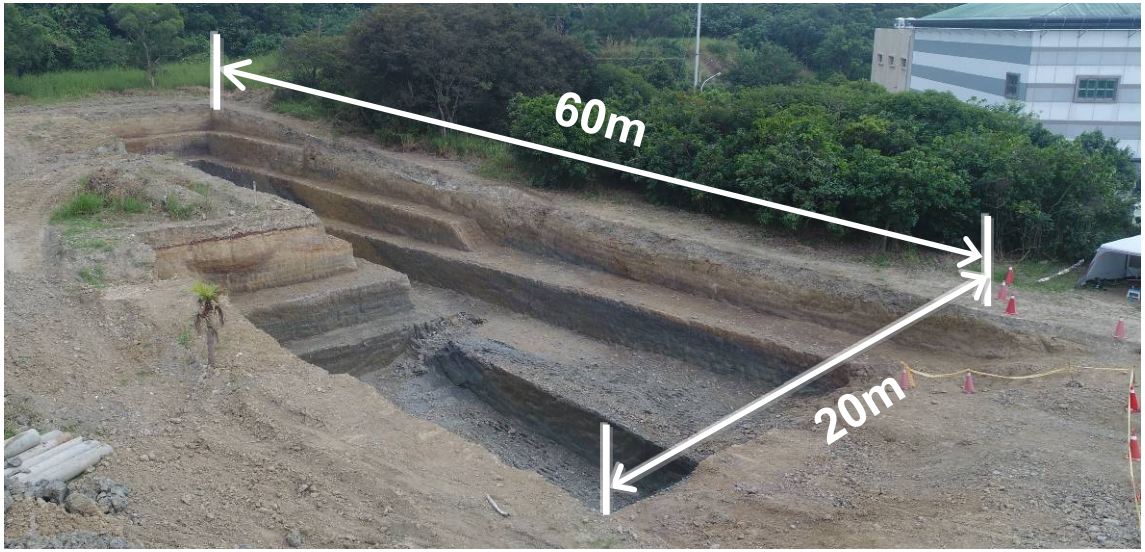
Trenching Site A – A bird-eye-view



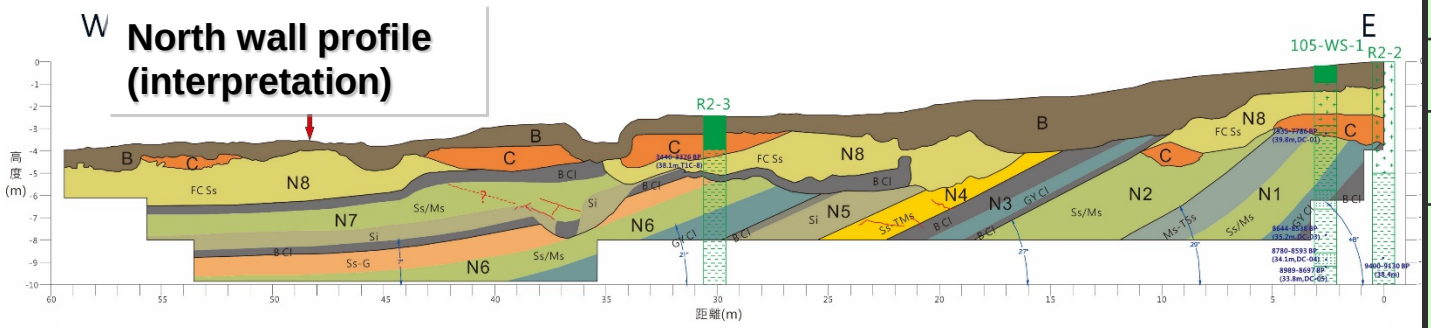
Trenching Site A

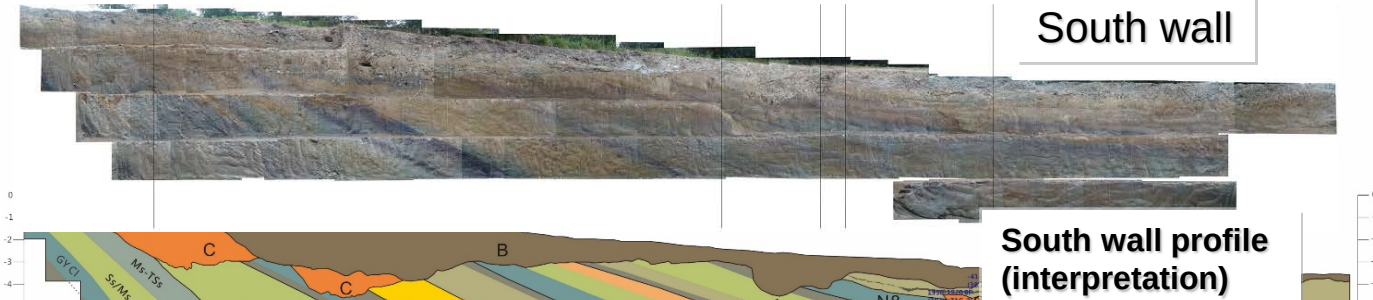


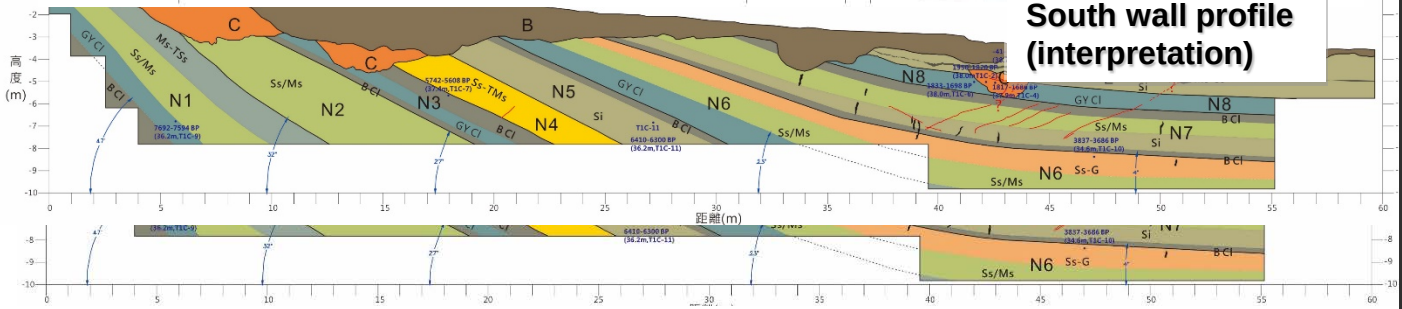




Trenching Site A- Profile of walls



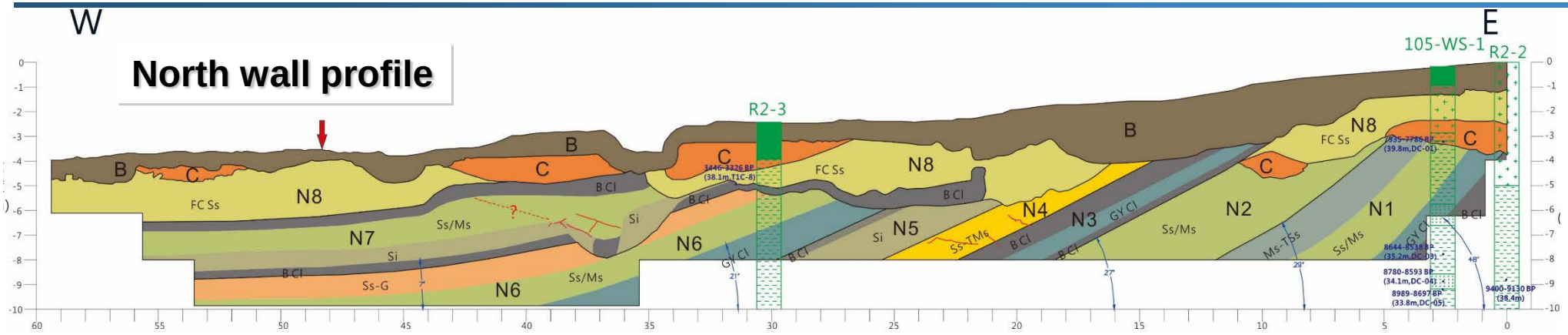




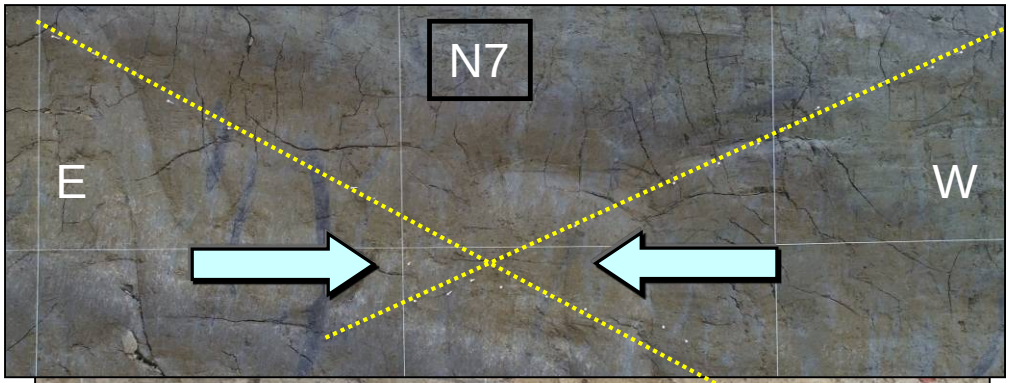
N1~N8：Holocene marine phase strata
C&L：Alluvium
B：Backfilled layer

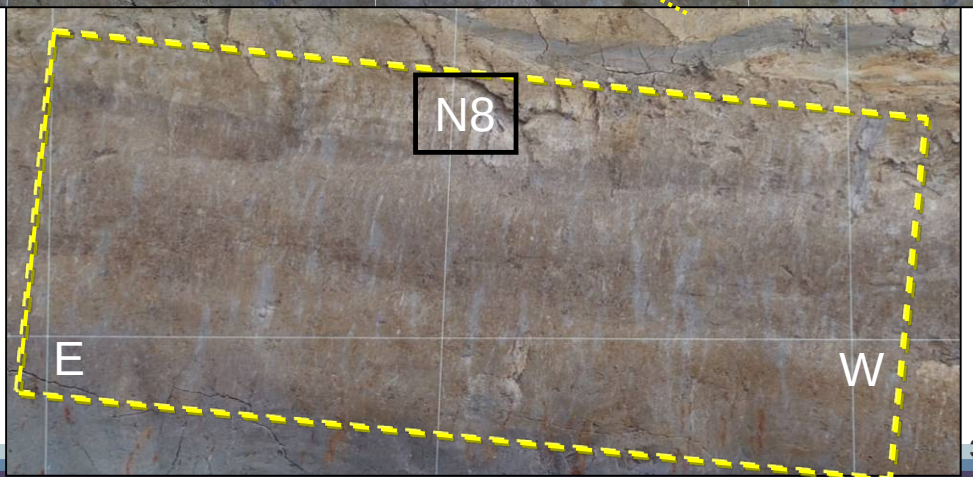
Layer	Lithology	Age(BP)
N1	Greenish clay	8989 – 7786
N2	Silt intercalate Clay	7935 – 7786
N3	Dark gray greenish clay	5742 – 5608
N4	Mud and Ss interlayer	-
N5	Brown clay	6410 – 6300
N6	Brown to Greenish clay	3837 – 3686
N7	Brown to Greenish clay	3446 – 3326
N8	Brown silt	1833 – 1698
C	River deposits	1950 – 1686
L	Mud and sand intercalated	-41 - -34

Geological structure interpretation

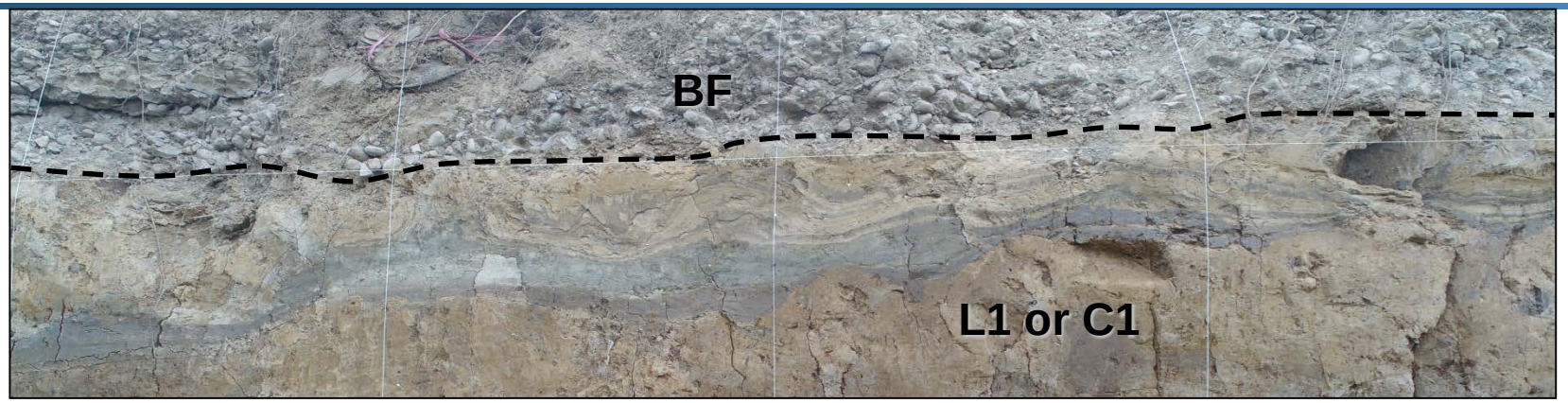


- Marine facies strata tilted. Dipping angle 50° on east decrease to 5 ° to west.
- Observed conjugated shear structures in 30~50°
- The main shear plane cut through the top N7 layer.
- Crack fillings can be found in layer N8. It might because the extension force made the crack perpendicular to the bedding of strata.
- The Holocene marine facies strata is suggested on the top of the hanging wall.

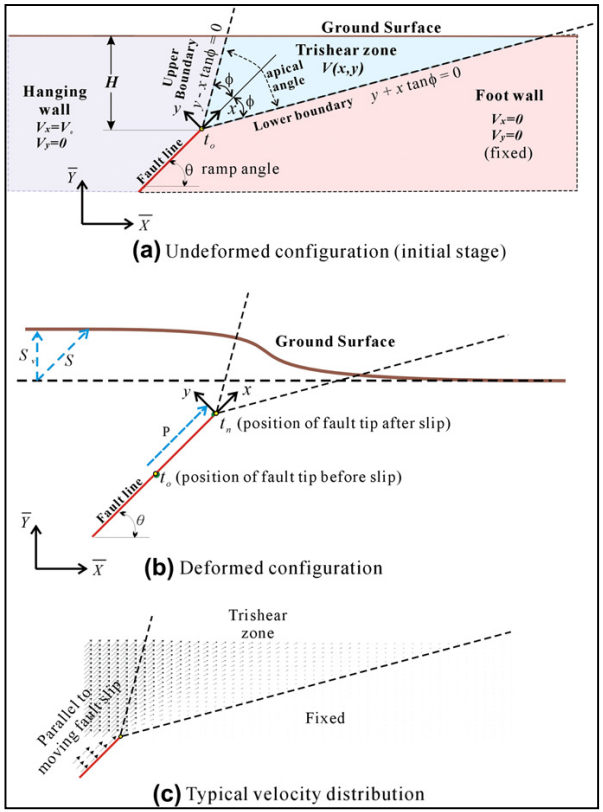




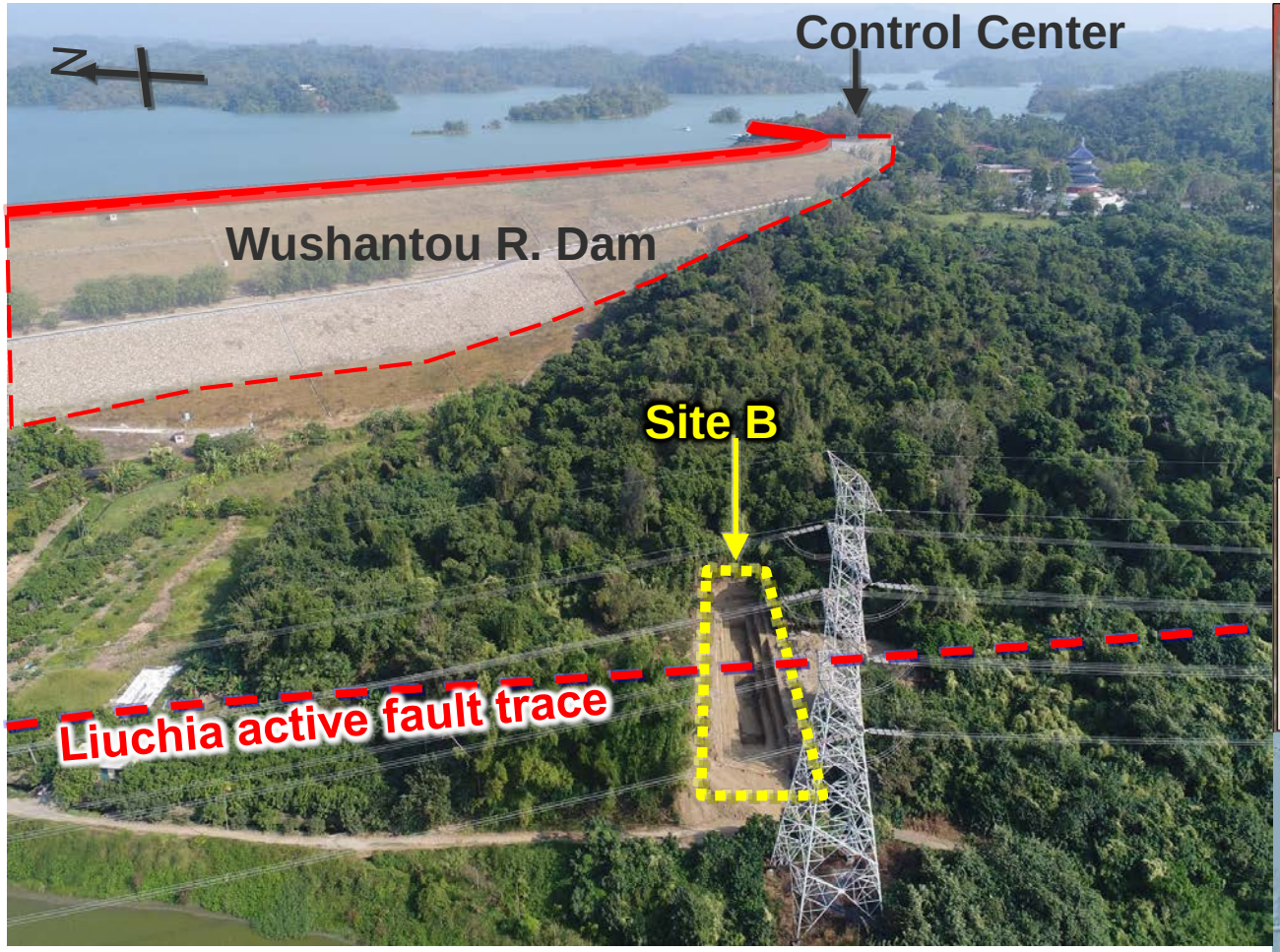
Geological structure interpretation

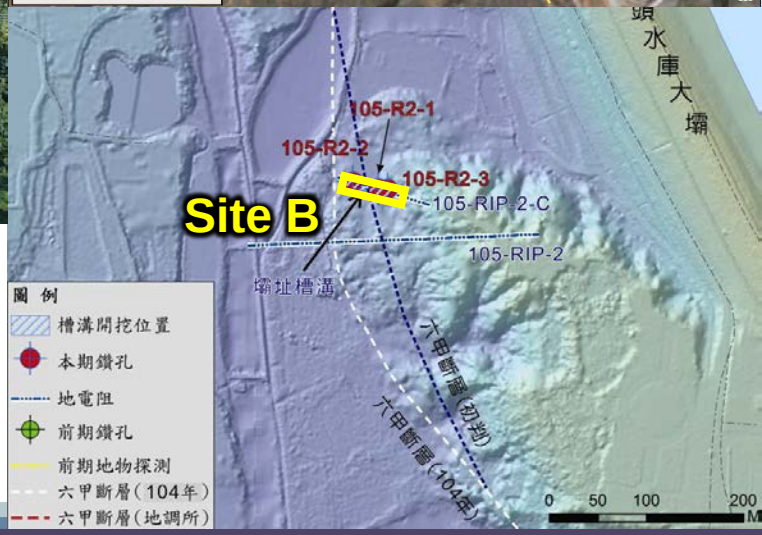


- The alluvium(L1 and C1) bedding is nearly flat without tilting.
- L1 and C1 can found some flexure layer with liquefaction.
- **This area located in the trishear zone of Liuchia fault.**
- **The faulting made the strata tilted and deformed strongly in the trishear zone.**
- The main fault didn't appear in our investigation.
- **Base on the evidences of shear structures and tilting layers, the Liuchia fault trace is buried.**
- **Deformed and flexure strata in recent 9000 year show that the Liuchia fault is an active fault, which can be categorized in the first class. (Active in Holocene 11,700 BP)**

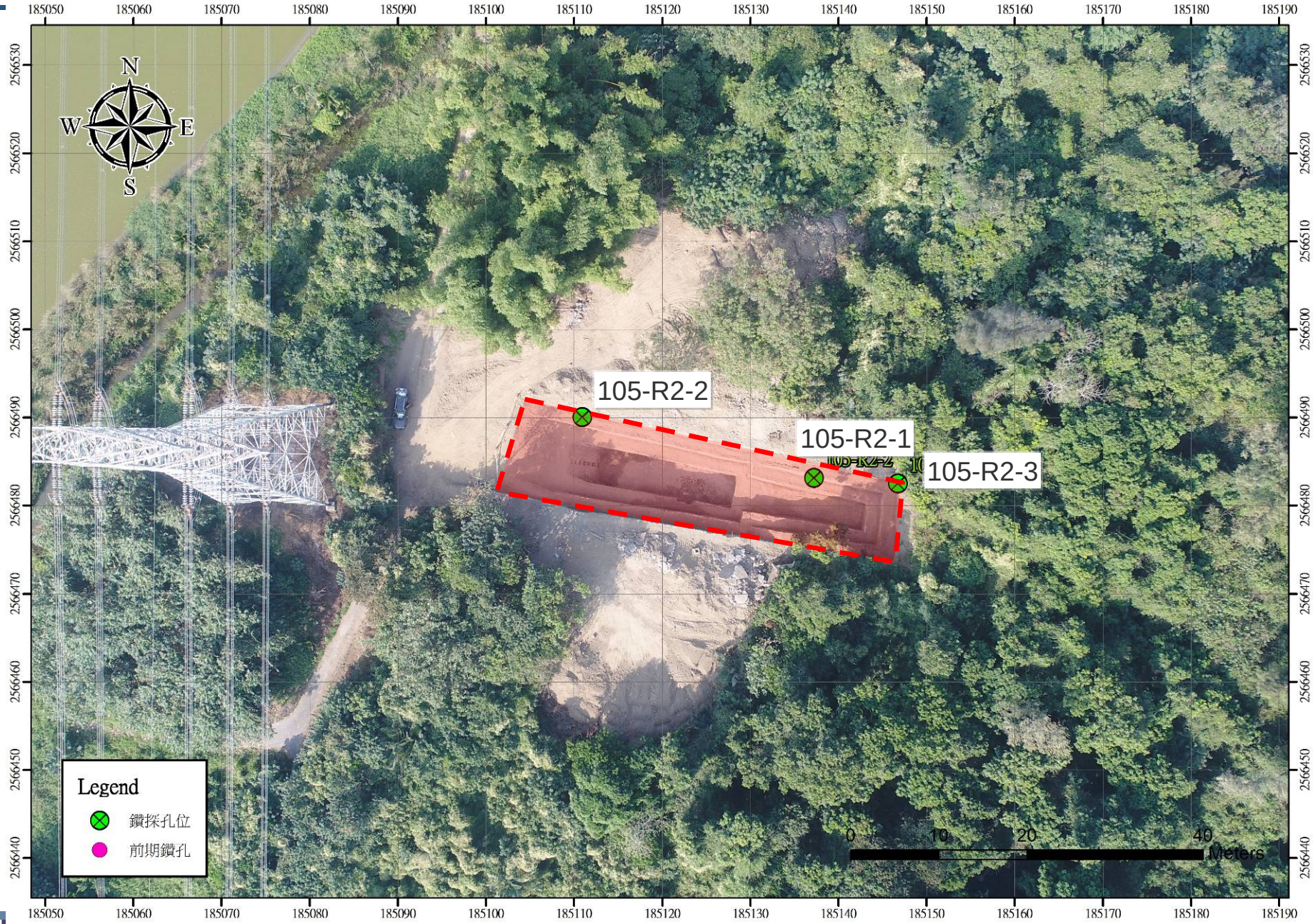


Site B trench (Down stream of the Dam)

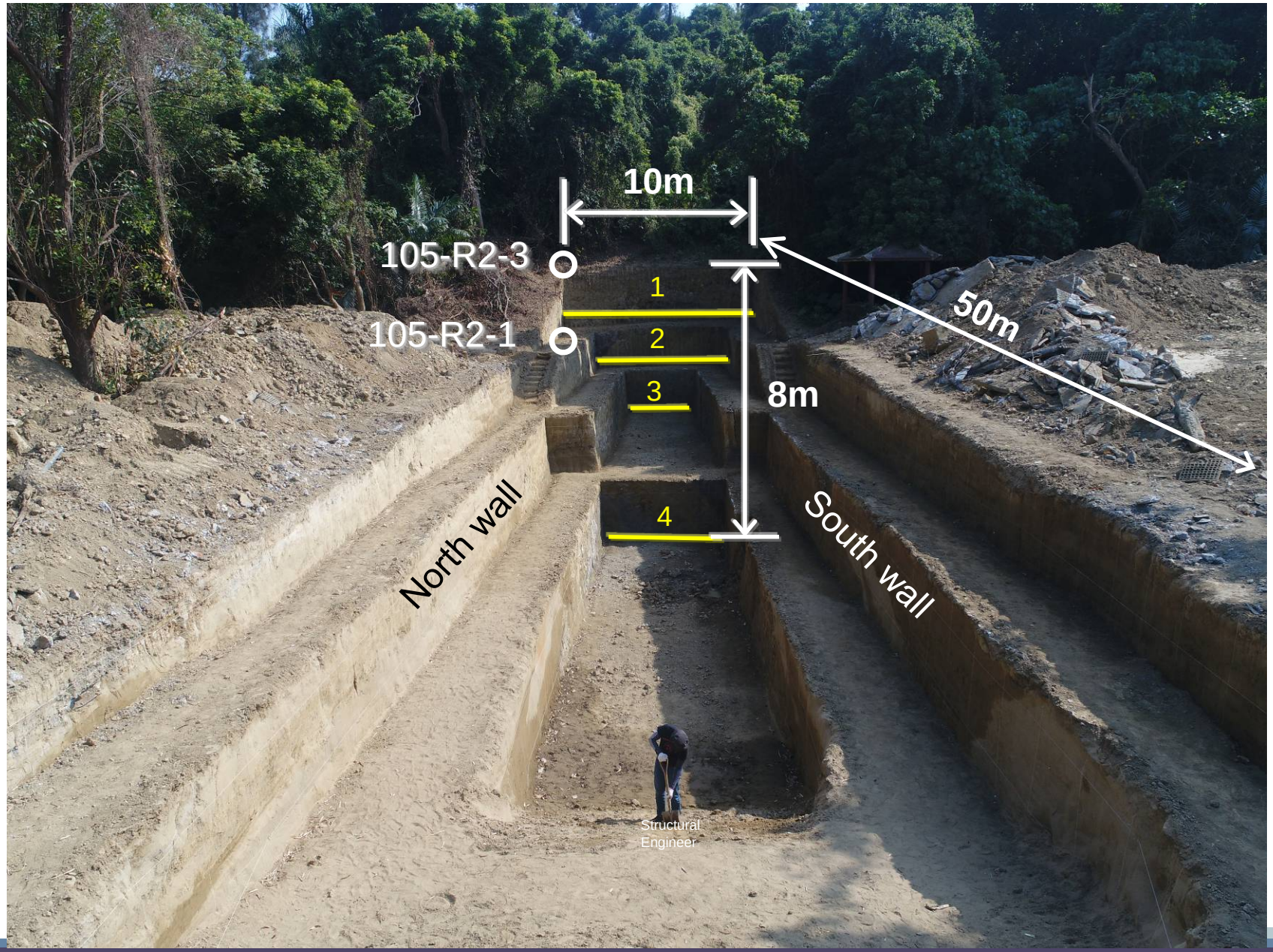




Site B trench – Bird-eye-view



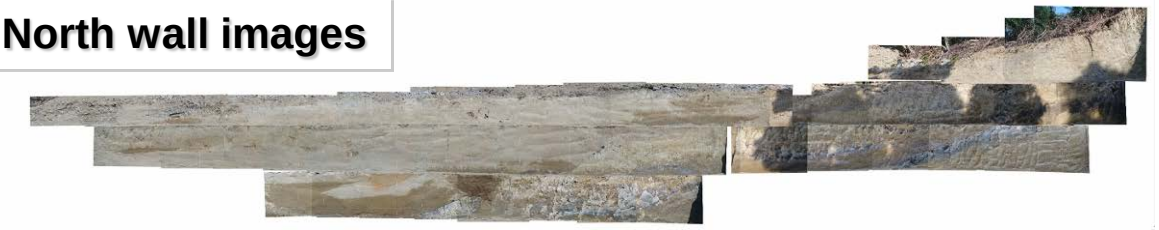
Site B trench



Site B trench walls profile

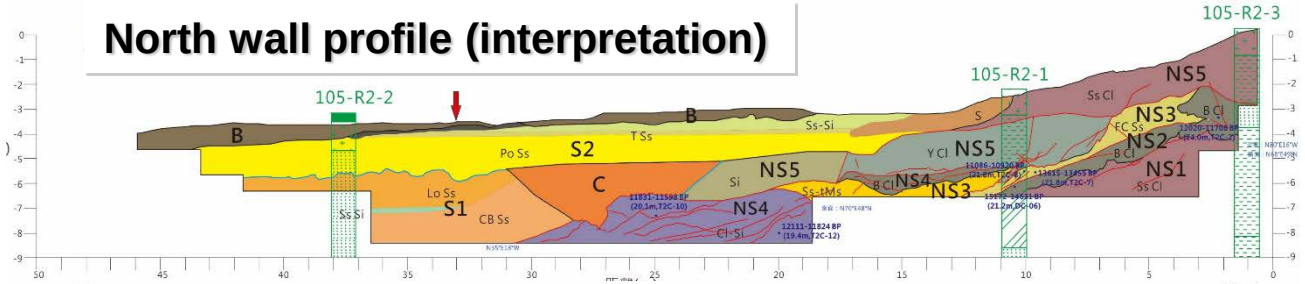
W E

North wall images



W E

North wall profile (interpretation)

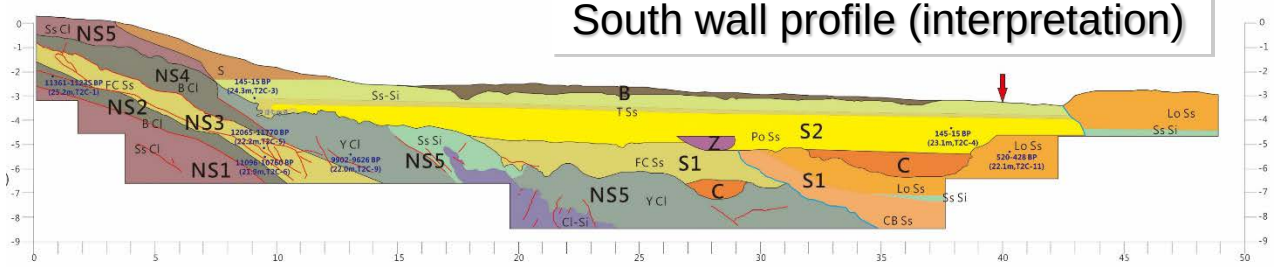


E W

South wall images

E W

South wall profile (interpretation)



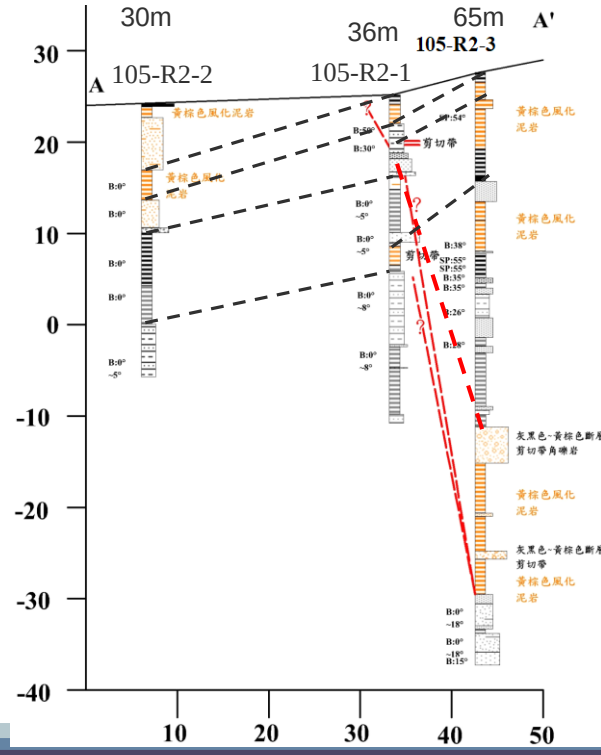
NS1~NS5：Holocene marine facies strata
S1~S2 ：Alluvium
B：Backfill

Layer	Lithology	Age (BP)
NS1	Brown soil with weathering lineation	Before 15172
NS2	Organic dark gray clay	15172 – 11235
NS3	Brown to greenish sand and clay intercalated	13615 - 10760
NS4	Dark gray organic clay	12111 - 11824
NS5	Brown sand intercalate with silt	9902 - 9626
S1	Loose sand	520 – 428
S2	Sand and silt intercalated	145 - 15

Site B trench Geological structure interpretation

North wall profile

- The alluvium with a unconformable contact on Holocene marine facies strata.
- The dip angle become lower from east to west. N1: 40° , NS5: 20~30°， S1: 0~10°， S2: horizontal gravels
- Shear structures (planes) can be found in Holocene marine facies strata with 20~50° dipping to west.
- Long-extend Shear structures can be found in NS2~NS4 layer, but it didn’t cut through the surface.

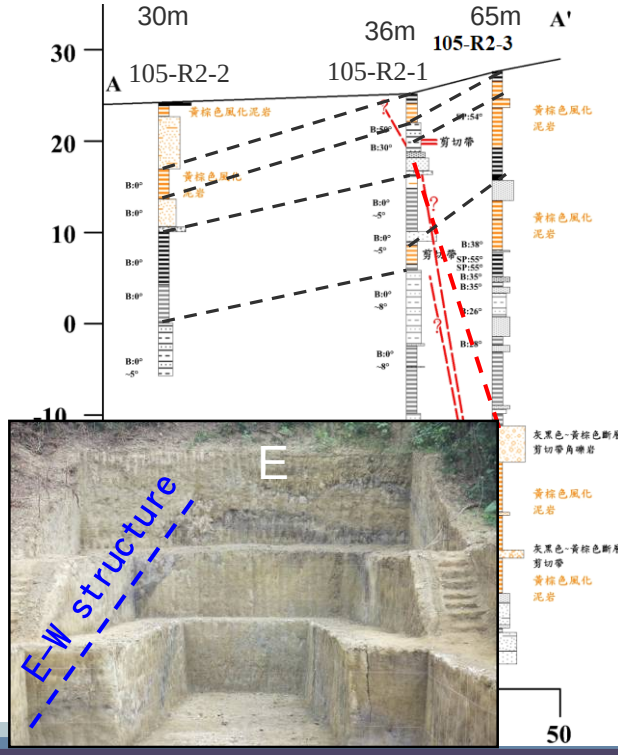


Site B trench Geological structure interpretation

North wall profile

- Shear plane found on the west side S1 and S2 layer, which dipping to east. It can extend to NS4 organic clay layer.
- There are several normal fault found in NS3 layer, which might be the fault dragging the Holocene marine facies strata.
- Slickensides found on the east of the wall, which the surface dipping to north.

- **There are no obvious stratigraphy throw showing in this trench site.**
- **Base on the evidence such as tilting strata, dense shear structures, the Liuchia fault trace is buried.**



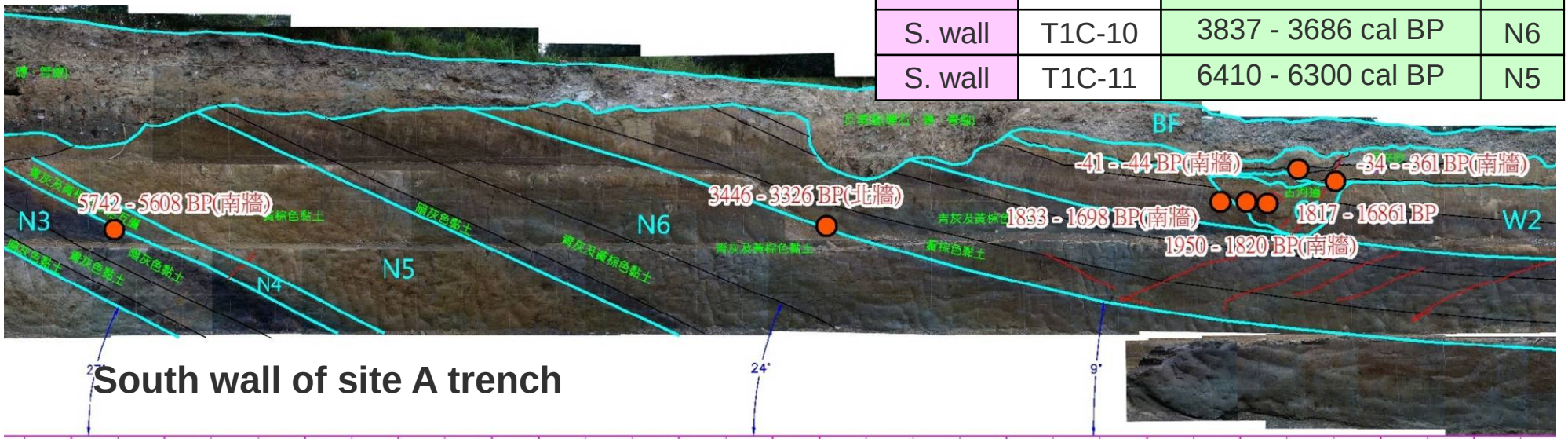
C14 dating results

- **30 sets of sample totally**
  - **1.11 sets** C14 dating results at site A trench (Wushantou power plant trech)
  - 2.7 sets C14 dating result from the drilling.
  - 3.12 sets C14 dating results from site B trench (down stream of the Dam)

* yr B.P.(year before present 1950)，
** Cal BP, calibrated by dendrochronology。

11 sets of C14 dating results from Site A trench

Location	Sample Name	Calibrated age (yr B.P.)	Layer No.
S. wall	T1C-1	-34 - -36 cal BP	L1
S. wall	T1C-2	1950 - 1820 cal BP	C1
S. wall	T1C-3	post AD 1950	-
S. wall	T1C-4	1817 - 1686 cal BP	C1
S. wall	T1C-5	-41 - -44 cal BP	L1
S. wall	T1C-6	1833 - 1698 cal BP	W2
S. wall	T1C-7	5742 - 5608 cal BP	N3
N. wall	T1C-8	3446 - 3326 cal BP	W1
S. wall	T1C-9	7692 - 7594 cal BP	N1
S. wall	T1C-10	3837 - 3686 cal BP	N6
S. wall	T1C-11	6410 - 6300 cal BP	N5



South wall of site A trench

C14 dating results

7 sets of C14 dating results from drilling

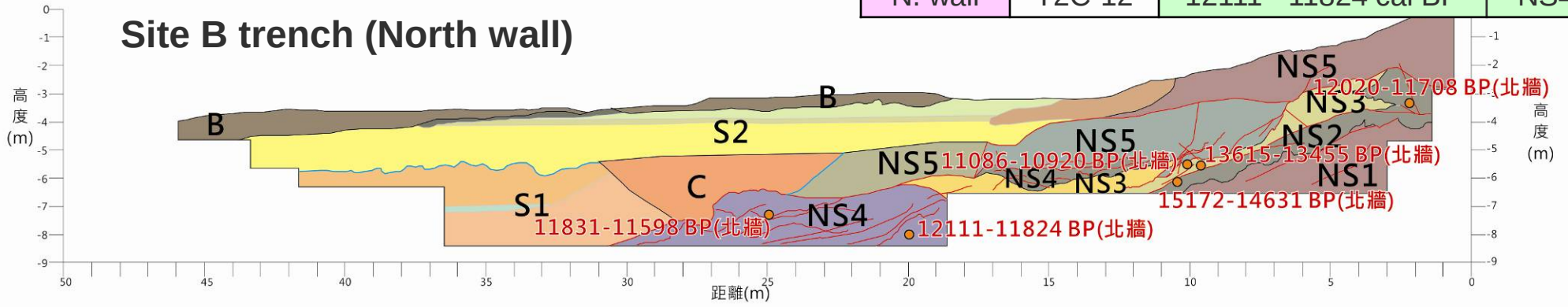
Drilling Number	Sample name	Sample depth (m)	Calibrated age (yr B.P.)
105-WS-1	DC-1	3.05	7935 - 7786 cal BP**
105-WS-1	DC-3	7.62	8644 - 8538 cal BP
105-WS-1	DC-4	8.7	8780 - 8593 cal BP
105-WS-1	DC-5	9.05	8989 - 8697 cal BP
105-R2-1	DC-6	3.95	15172 - 14631 cal BP
105-R2-3	DC-8	37.79	39016 - 37923 cal BP
105-R2-3	DC-9	40.95	25859 - 25369 cal BP

* yr B.P.(year before present 1950)，
** Cal BP, calibrated by dendrochronology。

12 sets of C14 dating results from Site B trench

Location	Sample Name	Calibrated age (yr B.P.)	Layer No.
S. wall	T2C-1	11361 - 11235 cal BP	NS2
N. wall	T2C-2	12020 - 11708 cal BP	NS2
S. wall	T2C-3	145 - 15 cal BP	S2
S. wall	T2C-4	145 - 15 cal BP	S2
S. wall	T2C-5	12065 - 11770 cal BP	NS3
S. wall	T2C-6	11096 - 10760 cal BP	NS3
N. wall	T2C-7	13615 - 13455 cal BP	NS3
N. wall	T2C-8	11086 - 10920 cal BP	NS3
S. wall	T2C-9	9902 - 9626 cal BP	NS5
N. wall	T2C-10	11831 - 11598 cal BP	NS4
S. wall	T2C-11	520 - 428 cal BP	S1
N. wall	T2C-12	12111 - 11824 cal BP	NS4

W



The Characteristics of Liuchia Fault

Topography and Geological setting

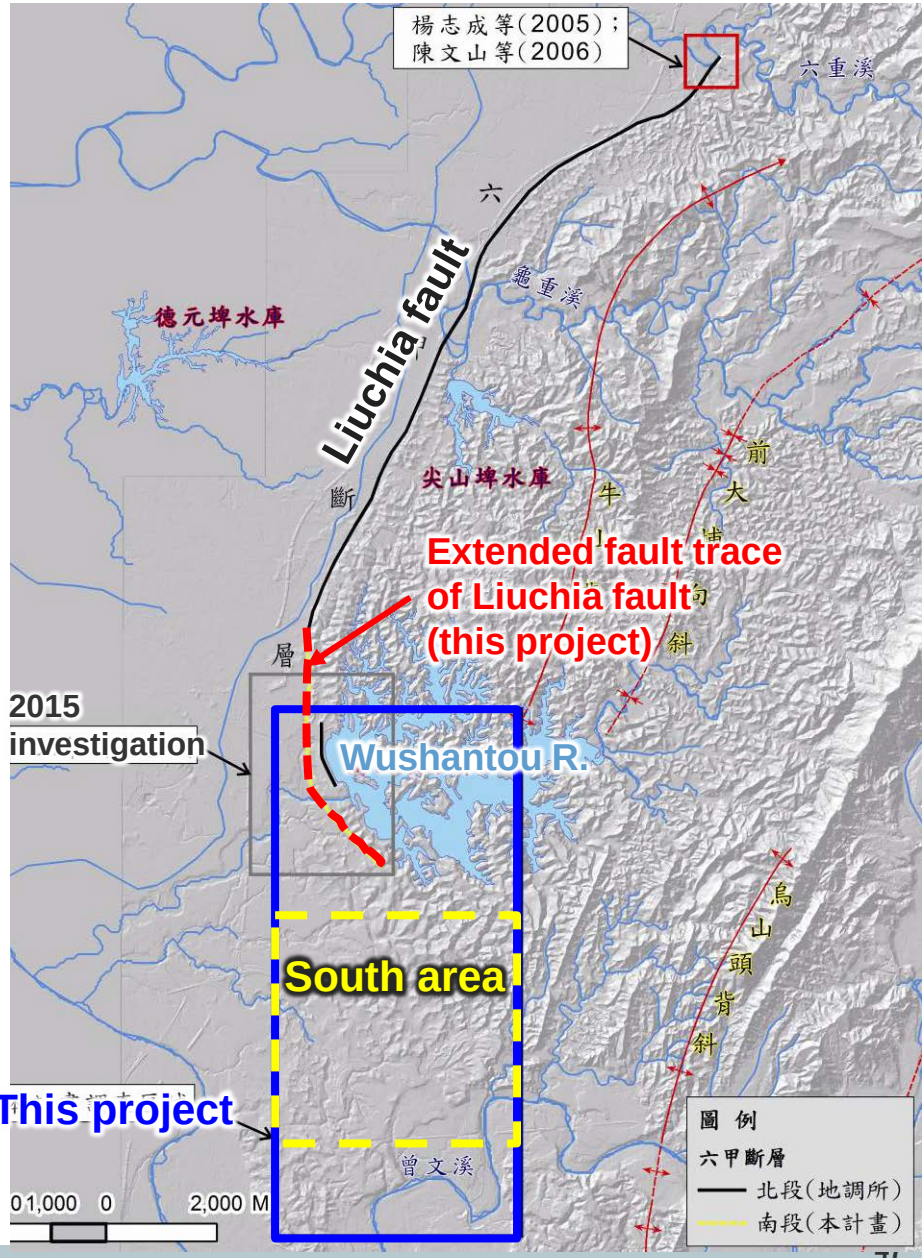
- The attitude of the rock formation on the hanging wall shows a arc shape with dipping to west 50◦high angle.
- On the footwall of the fault, the strata shows nearly flat with 0~10 ◦ dipping to west.

Location and length of Liuchia fault

☐Base on the results of 2015 and 2016, the main Liuchia fault did not cut through the surface.
☐It only caused the strata deformed.
☐At the south of the Wushantou R., the strata become tilted into high angle from west to east.
☐There are not evidence show that the fault propagate to the subsurface in the south part area according to our drilling results.

➢**The total length of Liuchia fault is about 13.3 km-long.**

➢**The southern part of the Liuchia fault is about 4.8 km-long (This project).**

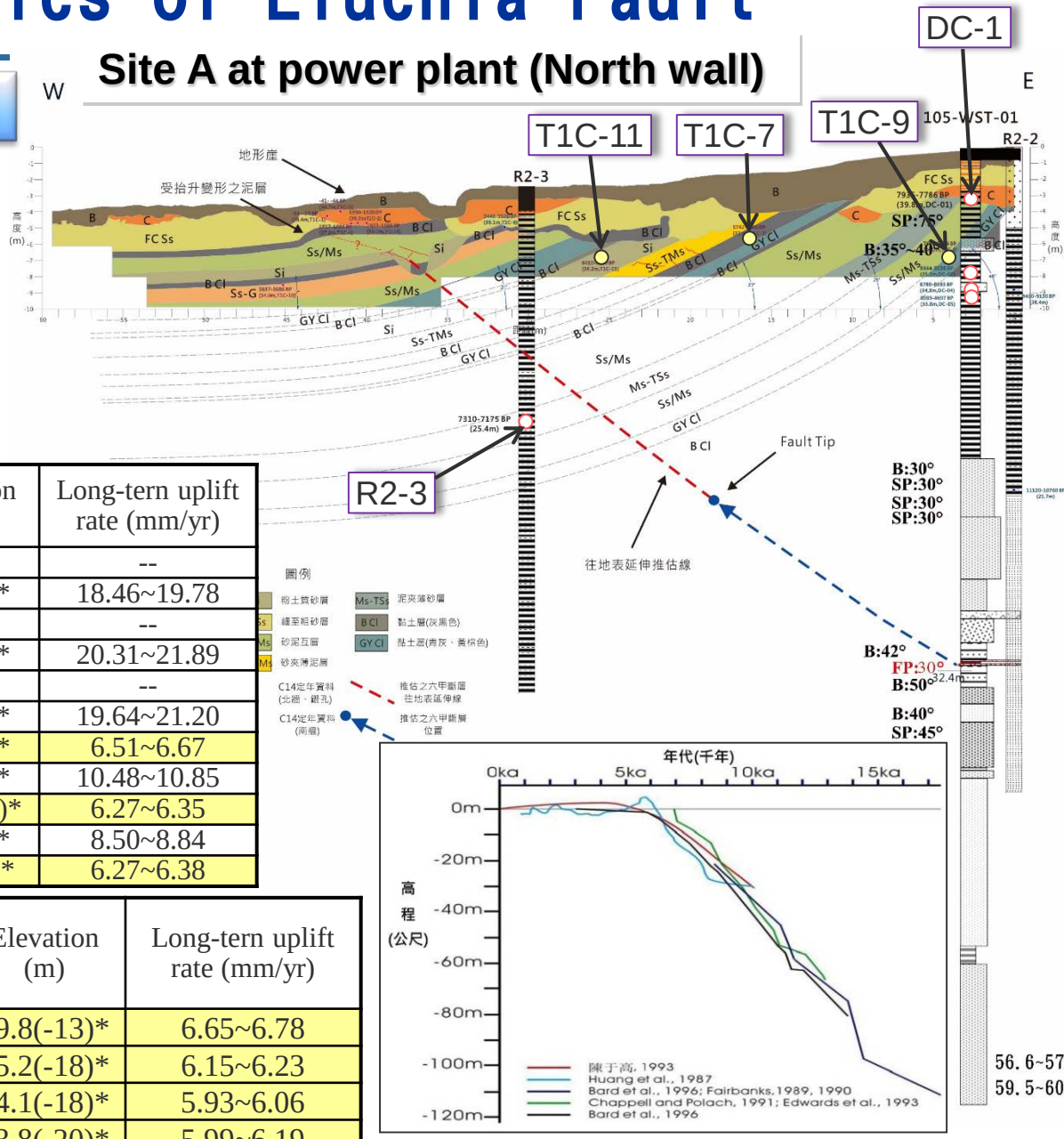


The Characteristics of Liuchia Fault

The slip rate of the Liuchia Fault

- Land facies strata shows up in the middle of the trench.
- Part of the layer are river deposits.
- The hanging wall uplift rate estimated via the data from the eastern north wall which is **5.93~6.78 mm/yr.**

Site A at power plant (North wall)



After 11,700 BP the sea level changing histogram

Location	Number	Calibrated age (yr B.P.)	Elevation (m)	Long-tern uplift rate (mm/yr)
South wall	T1C-1	-34 ~ -36 cal BP	38.4	--
	T1C-2	1950 ~ 1820 cal BP	38.0(2)*	18.46~19.78
	T1C-3	Post AD 1950	--	--
	T1C-4	1817 ~ 1686 cal BP	37.9(1)*	20.31~21.89
	T1C-5	-41 ~ -44 cal BP	38.7	--
	T1C-6	1833 ~ 1698 cal BP	38.0(2)*	19.64~21.20
	T1C-7	5742 ~ 5608 cal BP	37.4(0)*	6.51~6.67
	T1C-8	3446 ~ 3326 cal BP	38.1(2)*	10.48~10.85
	T1C-9	7692 ~ 7594 cal BP	36.2(-12)*	6.27~6.35
	T1C-10	3837 ~ 3686 cal BP	34.6(2)*	8.50~8.84
	T1C-11	6410 ~ 6300 cal BP	36.2(-4)*	6.27~6.38

Drilling No.	Sample Number	Sample depth (m)	Calibrated age (yr B.P.)	Elevation (m)	Long-tern uplift rate (mm/yr)
105-WS-1	DC-1	3.05	7935 – 7786 cal BP	39.8(-13)*	6.65~6.78
105-WS-1	DC-3	7.62	8644 – 8538 cal BP	35.2(-18)*	6.15~6.23
105-WS-1	DC-4	8.7	8780 – 8593 cal BP	34.1(-18)*	5.93~6.06
105-WS-1	DC-5	9.05	8989 – 8697 cal BP	33.8(-20)*	5.99~6.19
R2-3**	--	14.6	7175 – 7310 cal BP	25.42	4.9±0.2

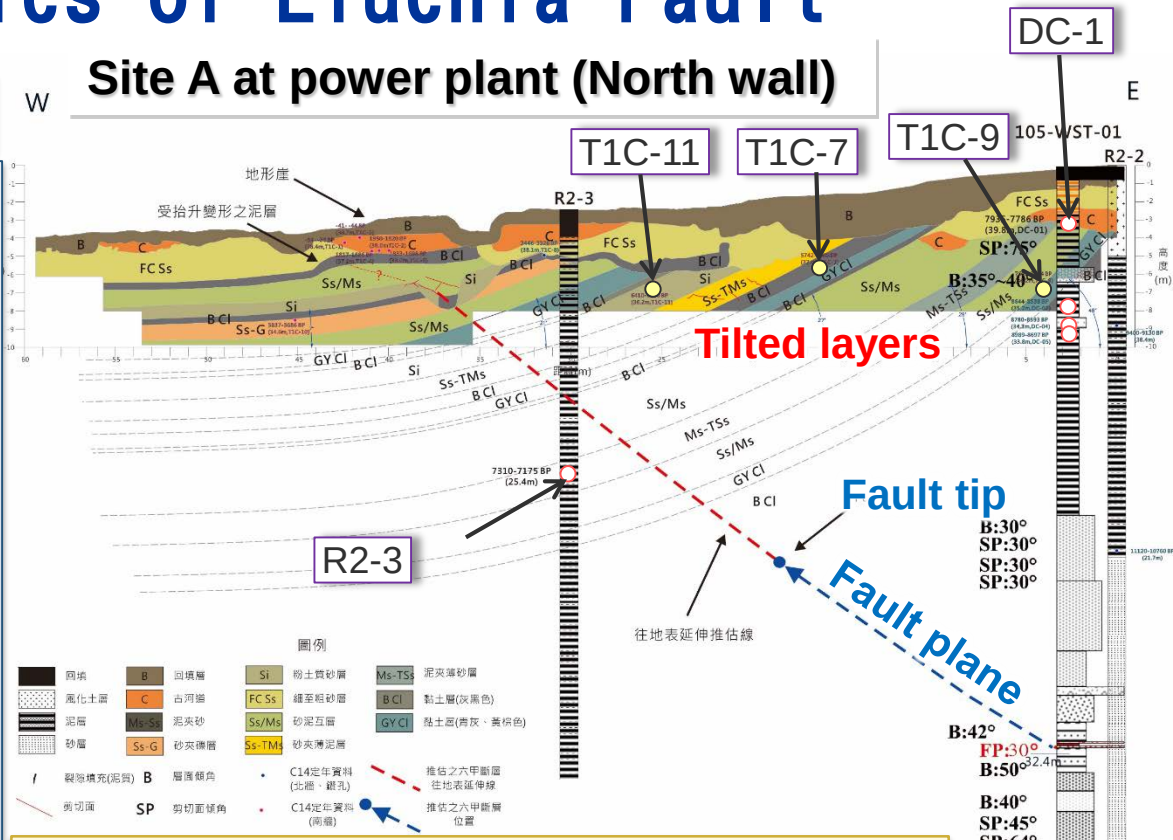
The Characteristics of Liuchia Fault

The slip rate of the Liuchia Fault

- It is hard to define the direct fault slip rate because of the Liuchia fault didn't cut through the subsurface.
- Via the deformed sedimented layer, we can estimate the uplift rate of the buried Liuchia fault.
- DC-01 age is 7835~7786 Cal BP
- R2-3 age is 7310~7175 Cal BP, that means when the layer start to deposit, DC-01's elevation is lower than R2-3' s.
- Because of the faulting event let the DC-01 thrust up onto the R2-3's elevation.

➢ The 105-WS-1 well at depth 32.3m has fault gouge and breccia contacts, we can estimate the fault surface is dipping ~30°

➢ Previous research presented that the footwall long-tern uplift rate is 4.9±0.2 mm/yr（R2-3）, hence, the Liuchia fault's long-tern slip rate can be **3.10~4.16 mm/yr**



- ✓ Our estimation of long-tern slip rate is lower than the rate which Young et al.(2005) and Chen et al.(2006) published(11.0~12.7 mm/yr).
- ✓ **It suggests that our study area might be the end tip of Liuchia fault.**
- ✓ **The fault did not cut through the surface with buried fault trace. Only cause the subsurface layer deformed and tilted.**

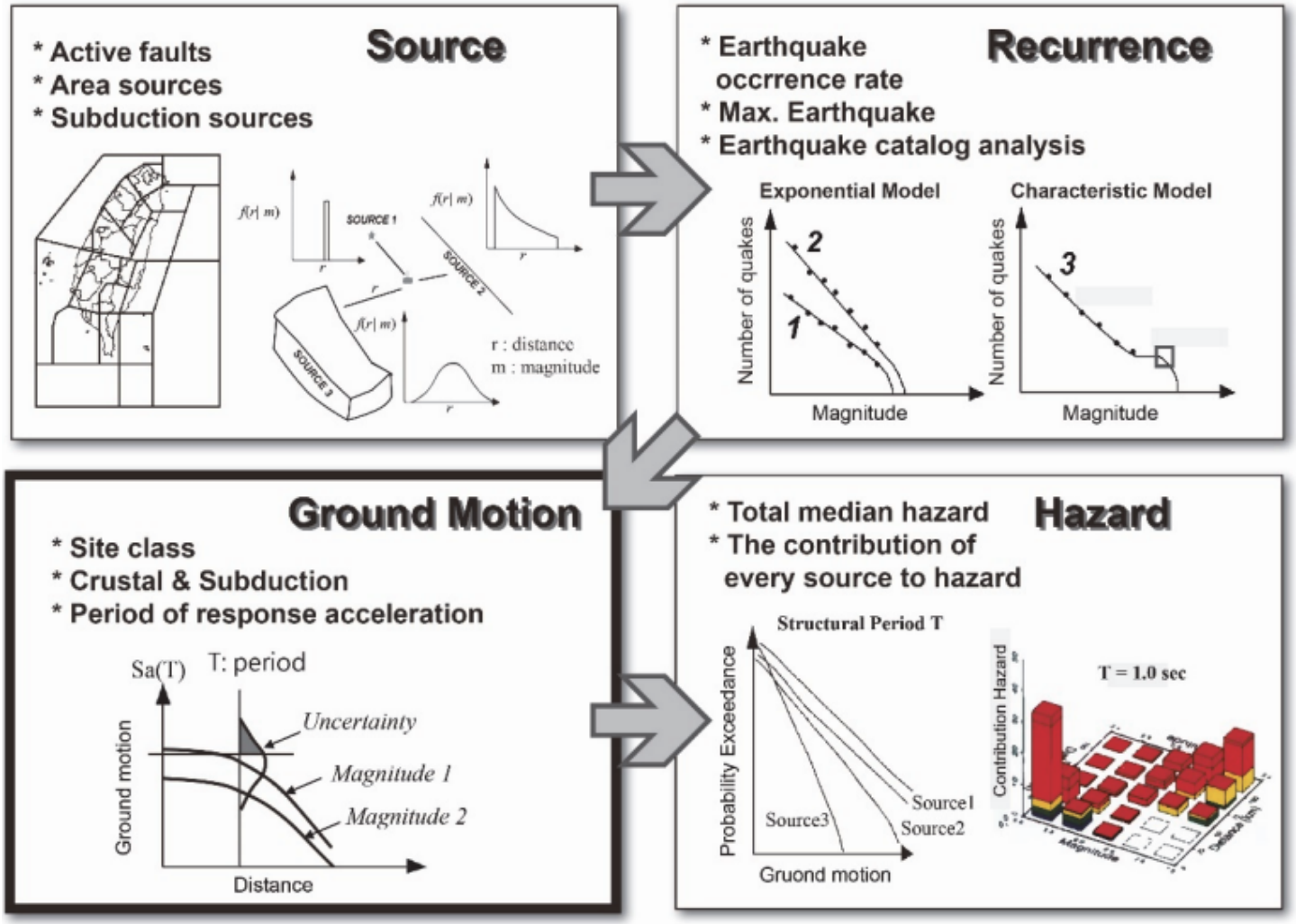
The Characteristics of Liuchia Fault

Categories	Characteristics	Source
Fault trace length (km)	16	CGS(2012)
	13.3	MOEA(2017)
	18.4	Chianan Irrigation(2015)
	18.1 (13.3(north)+4.8(south))	**This project**
Fault plane angle	30	Young et al.(2005)
	60	Chianan Irrigation(2015)
	30	This project
Closest distance to Wushantou R.	240	Chianan Irrigation(2015)
	240	**This project**
Longtern slip rate (mm/yr)	11	Young et al.(2005)
	12.7	Chen et al.(2006)
	1.4~2.8	Chianan Irrigation(2015)
	3.10~4.16	**This project**
Mobility (activity)	<7,000	Chianan Irrigation(2015)
	< 11,700 BP.	**This project**

Design Earthquake Analysis

Dam Hazard Analysis-design earthquake analysis

The goal of probabilistic seismic hazard analysis (PSHA) is **to quantify the rate (or probability) of exceeding various ground-motion levels at a site (or a map of sites) given all possible earthquakes**.



PSHA- flow chart

Yen et al. (2019)

Dam Hazard Analysis-design earthquake analysis

Fault Source

2012 Taiwan Fault Distribution Map (CGS) ➔

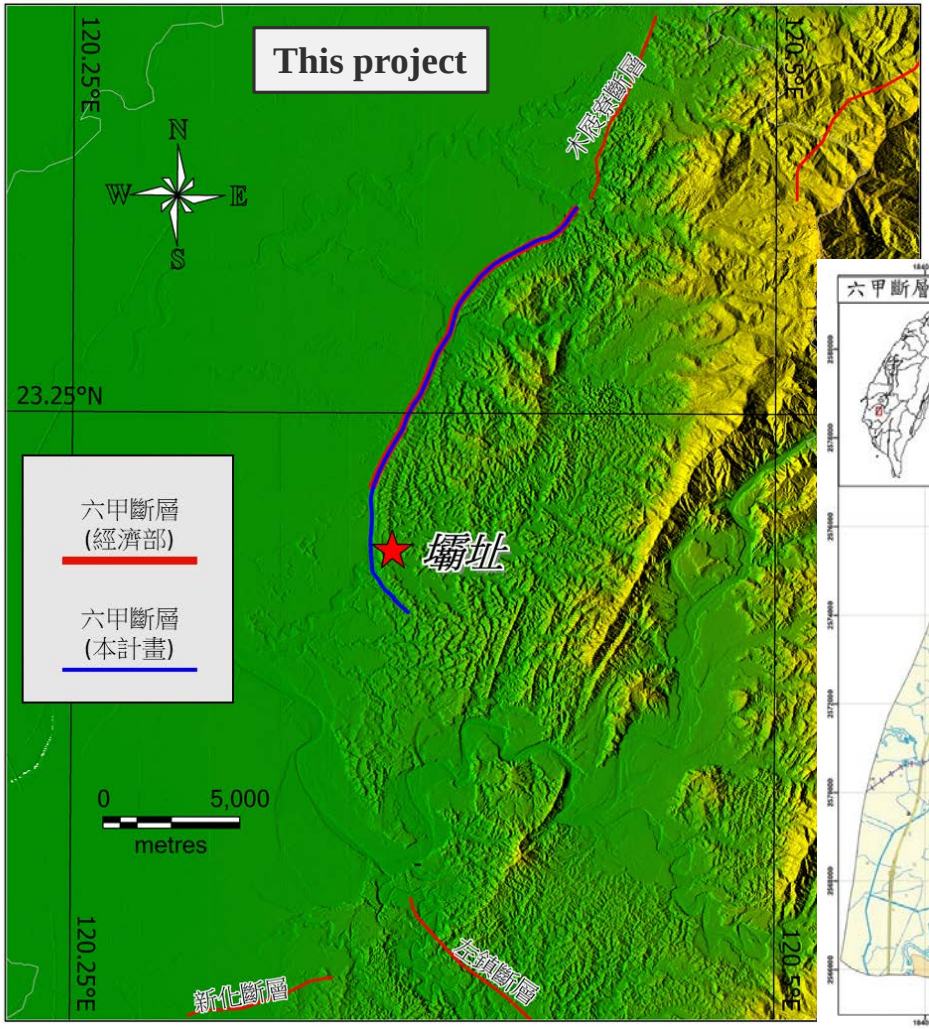
1. This project (trenching and drilling data)、

2. Previous project (**六甲斷層調查及烏山頭水庫安全影響評估與因應對策**)、

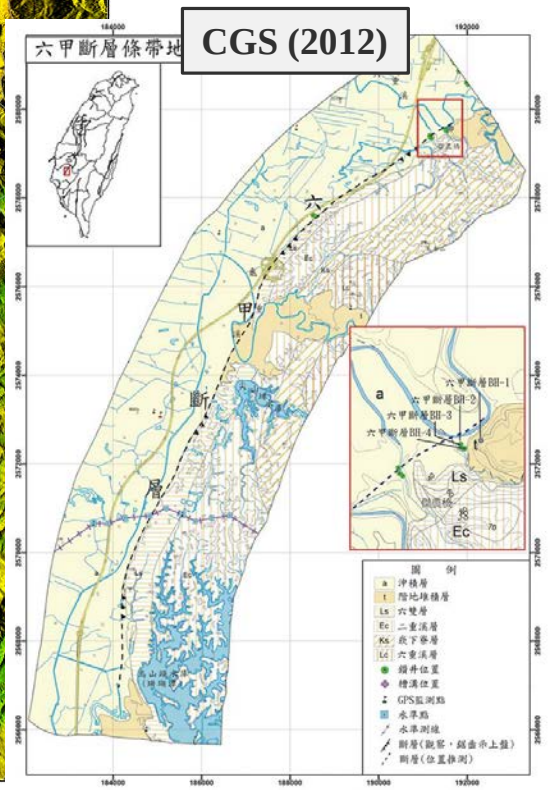
3. NCU Graduate Institute of Applied Geology (NCUAPI, 2016)、

4.**斷層活動性觀測性研究** (CGS, 2014-2016)

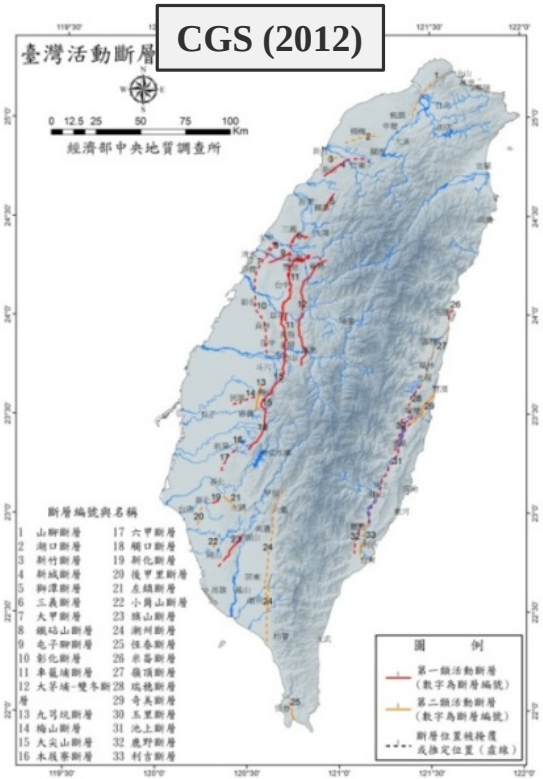
5. and the active fault parameters in various academic studies.



CGS (2012)



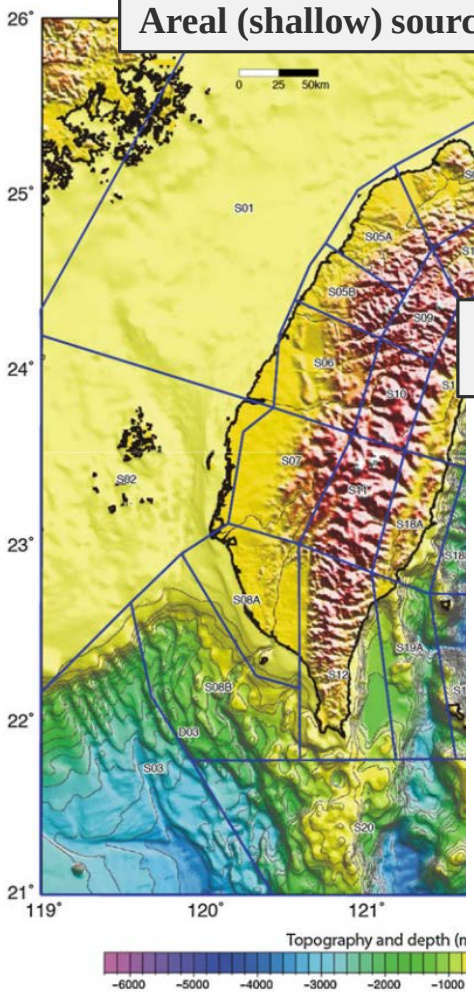
CGS (2012)



Dam Hazard Analysis-design earthquake analysis

Areal source

Update Areal (shallow) source to Cheng et al. (2015)

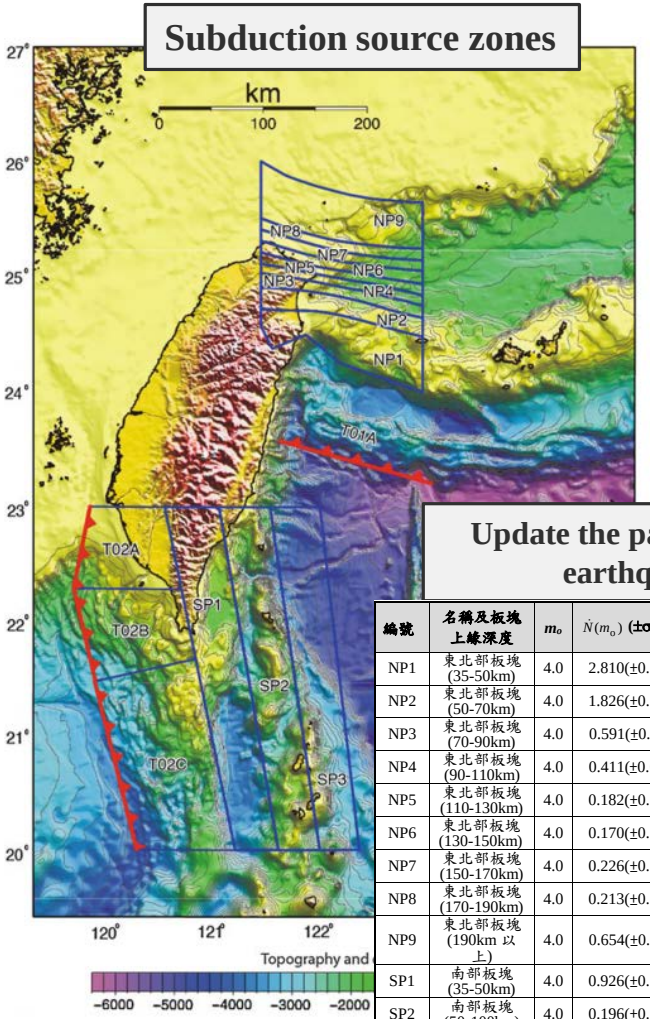


Update the parameters with new earthquake catalog

NO	m_o	$N(m_o)$ $(\pm\sigma_{N(m_o)})$	$b(\pm\sigma_b)$	m_u(括號中為權重)
S01	3.5	0.986(±0.149)	0.913(±0.127)	6.5 (0.2) 6.6 (0.6) 6.7 (0.2)
S02	3.5	0.820(±0.136)	0.779(±0.134)	6.5 (0.2) 6.6 (0.6) 6.7 (0.2)
S03	3.5	0.689(±0.124)	0.785(±0.169)	6.5 (0.2) 6.6 (0.6) 6.7 (0.2)
S04	2.5	3.330(±0.355)	0.896(±0.083)	5.0(1.0)
S05A	2.5	4.728(±0.428)	1.134(±0.091)	5.0(1.0)
S05B	2.5	5.966(±0.473)	0.858(±0.056)	5.0(1.0)
S06	2.5	8.832(±0.570)	0.750(±0.038)	5.0(1.0)
S07	3	4.880(±0.387)	0.609(±0.044)	5.0(1.0)
S08A	2.5	7.379(±0.521)	0.747(±0.044)	5.0(1.0)
S08B	2.5	12.380(±0.690)	1.046(±0.050)	6.5 (0.2) 6.6 (0.6) 6.7 (0.2)
S09	2.5	1.625(±0.238)	0.524(±0.075)	6.7 (0.2) 6.9 (0.6) 7.1 (0.2)
S10	3.5	0.813(±0.135)	0.721(±0.127)	6.5 (0.2) 6.7 (0.6) 6.9 (0.2)
S11	3.5	1.531(±0.186)	0.908(±0.110)	6.5(1.0)
S12	2.5	17.840(±0.802)	0.657(±0.024)	5.0(1.0)
S13	3	1.645(±0.225)	0.636(±0.072)	6.3 (0.2) 6.5 (0.6) 6.7 (0.2)
S14A	2.5	2.702(±0.313)	0.689(±0.067)	6.7 (0.2) 6.9 (0.6) 7.1 (0.2)
S14B	3.5	2.386(±0.227)	0.583(±0.047)	7.4 (0.2) 7.6 (0.6) 7.8 (0.2)
S14C	3.5	3.524(±0.279)	0.690(±0.049)	7.4 (0.2) 7.6 (0.6) 7.8 (0.2)
S15	3.5	2.644(±0.239)	0.597(±0.045)	7.0(1.0)
S16	3.5	5.487(±0.344)	0.594(±0.033)	7.0(1.0)
S17A	3.5	2.855(±0.249)	0.628(±0.047)	5.0(1.0)
S17B	3.5	1.671(±0.193)	0.727(±0.089)	7.3 (0.2) 7.5 (0.6) 7.7 (0.2)
S18A	3.5	2.645(±0.240)	0.636(±0.052)	5.0(1.0)
S18B	3.5	2.105(±0.217)	0.710(±0.078)	7.3 (0.2) 7.5 (0.6) 7.7 (0.2)
S19A	3.5	4.414(±0.312)	0.711(±0.043)	7.3 (0.2) 7.5 (0.6) 7.7 (0.3)
S19B	3.5	2.026(±0.212)	0.733(±0.065)	7.3 (0.2) 7.5 (0.6) 7.7 (0.3)
S20	3.5	3.600(±0.283)	0.757(±0.051)	7.1 (0.2) 7.3 (0.6) 7.5 (0.2)
S21	3.5	7.904(±0.420)	0.761(±0.034)	7.1 (0.2) 7.3 (0.6) 7.5 (0.2)

Subduction source

Add Subduction source from Cheng et al. (2015)



Update the parameters with new earthquake catalog

編號	名稱及板塊上緣深度	m_o	$\dot{N}(m_o)$ $(\pm\sigma_{\dot{N}(m_o)})$	$b(\pm\sigma_b)$	m_u(括號中為權重)
NP1	東北部板塊(35-50km)	4.0	2.810(±0.247)	0.911(±0.068)	7.5 (0.2) 7.7 (0.6) 7. 9 (0.2)
NP2	東北部板塊(50-70km)	4.0	1.826(±0.199)	0.871(±0.090)	7.5 (0.2) 7.7 (0.6) 7. 9 (0.2)
NP3	東北部板塊(70-90km)	4.0	0.591(±0.111)	0.738(±0.121)	7.6 (0.2) 7. 8 (0.6) 8.0 (0.2)
NP4	東北部板塊(90-110km)	4.0	0.411(±0.093)	0.725(±0.143)	7.6 (0.2) 7. 8 (0.6) 8.0 (0.2)
NP5	東北部板塊(110-130km)	4.0	0.182(±0.060)	0.583(±0.174)	7.6 (0.2) 7. 8 (0.6) 8.0 (0.2)
NP6	東北部板塊(130-150km)	4.0	0.170(±0.059)	0.582(±0.234)	7.6 (0.2) 7. 8 (0.6) 8.0 (0.2)
NP7	東北部板塊(150-170km)	4.0	0.226(±0.068)	0.647(±0.165)	7.6 (0.2) 7. 8 (0.6) 8.0 (0.2)
NP8	東北部板塊(170-190km)	4.0	0.213(±0.068)	0.776(±0.359)	7.6 (0.2) 7. 8 (0.6) 8.0 (0.2)
NP9	東北部板塊(190km 以上)	4.0	0.654(±0.118)	0.810(±0.142)	7.6 (0.2) 7. 8 (0.6) 8.0 (0.2)
SP1	南部板塊(35-50km)	4.0	0.926(±0.139)	0.577(±0.124)	7.5 (0.2) 7.7 (0.6) 7. 9 (0.2)
SP2	南部板塊(50-100km)	4.0	0.196(±0.206)	0.905(±0.084)	7.6 (0.2) 7. 8 (0.6) 8.0 (0.2)
SP3	南部板塊(100-180km)	4.0	1.212(±0.162)	0.832(±0.106)	7.6 (0.2) 7. 8 (0.6) 8.0 (0.2)

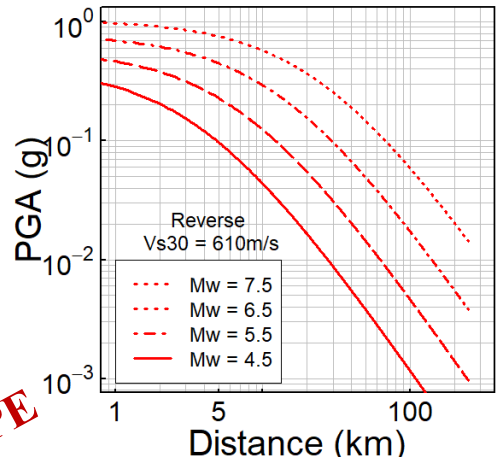
Dam Hazard Analysis-design earthquake analysis

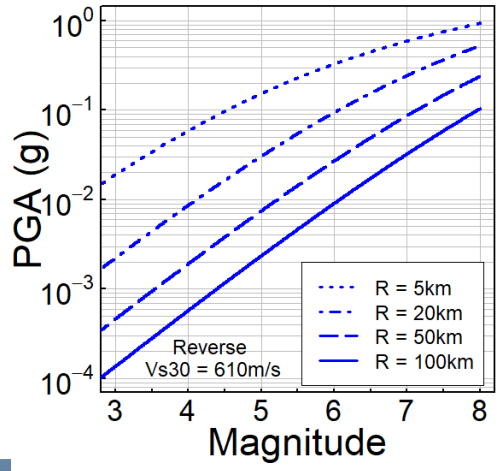
GMPE (Ground Motion Prediction Equation)

✓ A **site dependent GMPE** is built for the Wushantou Reservoir.

We analysis with the earthquake data near the dam and the geological condition of which is similar to the dam to reduce the variability of ground motion, and it also decreases the standard deviation of GMPE in order to estimate reasonable ground motions level precisely.

New GMPE





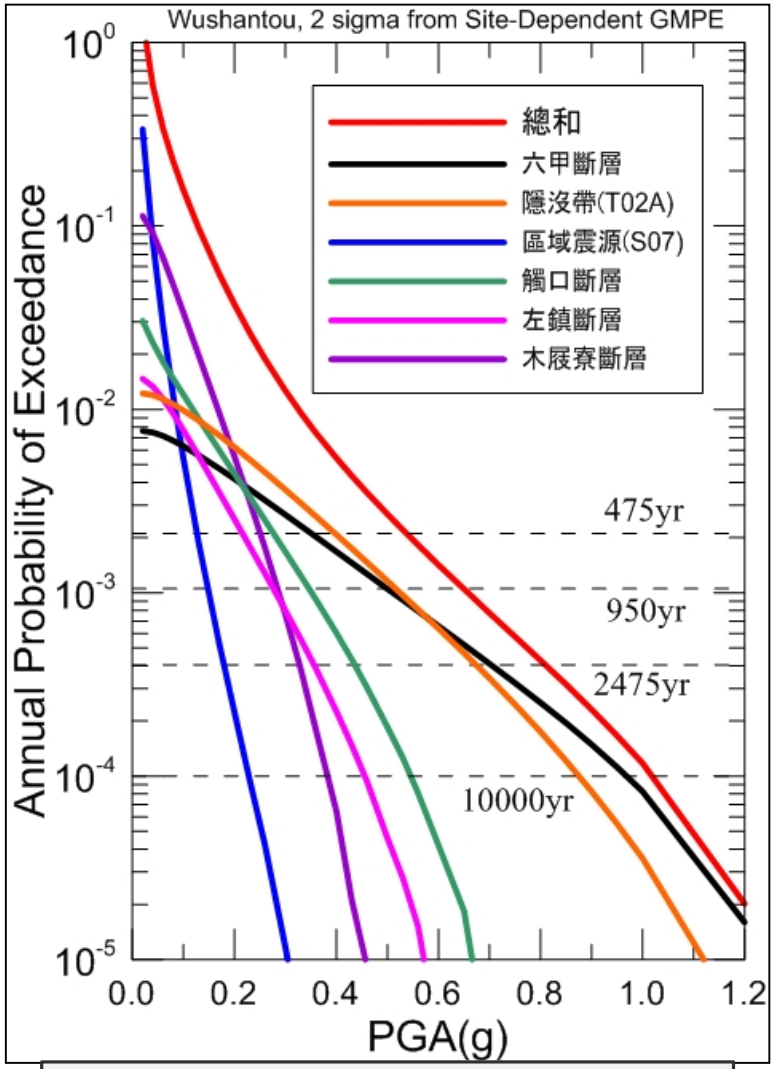
Strong motion stations within 70 km away from dam with similar geological conditions.

Dam Hazard Analysis-design earthquake analysis

Seismic hazard analysis

✓ This project followed the rules in 水利建造物檢查及安全評估技術規範蓄水與引水篇 (2008).

Project	Method	Control fault	The shortest distance of Control fault	Magnitude		PGA (g)	Return period (yr)	Adopted standard deviation
4th	DSHA	Liuchia Fault	0.2 km	MCE	6.9	0.75	-	-
	PSHA	Areal source Fault source		DBE	-	0.62	950	not specified
				OBE		0.53	475	not specified
	-			MDE	-	0.75	-	-
Previous project	DSHA	Liuchia Fault	0.24 km	MCE	6.82	0.84	-	-
	PSHA	Areal source Fault source		MCE	-	1.10	10000	not specified
				DBE		0.78	950	not specified
				OBE		0.70	475	not specified
	-			MDE	-	0.84	-	-
This project	DSHA	Liuchia Fault	0.24 km	MCE	6.82	0.68	-	-
	PSHA	Areal source Fault source		MCE	-	0.66~1.26	10000	0.66 · truncated 1*σ 1.02 · truncated 2*σ 1.26 · truncated 3*σ
				DBE		0.46~0.73	950	0.46 · truncated 1 *σ 0.65 · truncated 2 *σ 0.73 · truncated 3 *σ
				OBE		0.42~0.60	475	0.42 · truncated 1*σ 0.54 · truncated 2*σ 0.60 · truncated 3*σ
	-			MDE	-	0.66~1.26	-	-



Seismic hazard curve for Wushantou Reservoir

Dam Hazard Analysis-design earthquake analysis

Seismic coefficients

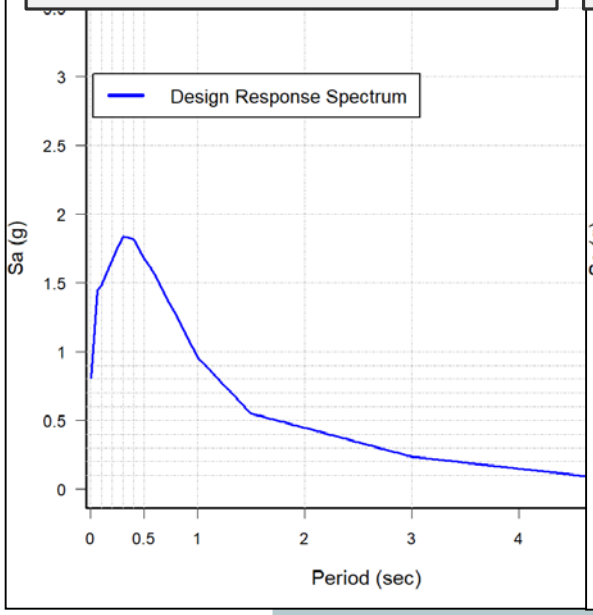
✓ **This project follows the rules in 水利建造物檢查及安全評估技術規範蓄水與引水篇 (2008), and obtain the seismic coefficient by interpolating.**

Seismic coefficients for the Wushantou Reservoir

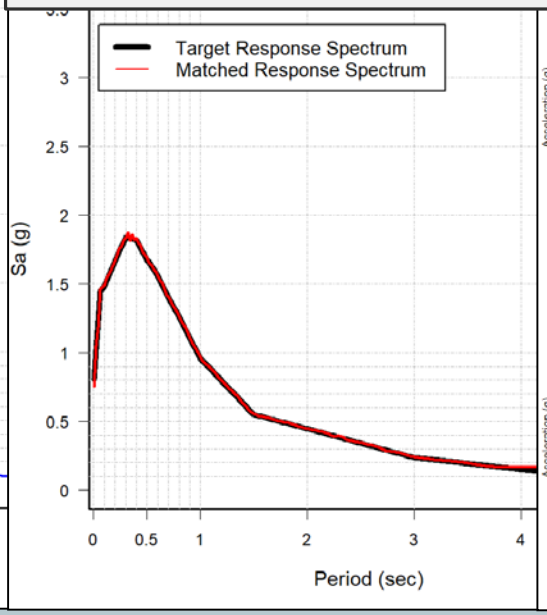
Design earthquake magnitude	PGA (g)	Seismic coefficients	
		Horizontal	Vertical
MCE	**0.81**	**0.24**	**0.16**
DBE	**0.65**	**0.20**	**0.13**
OBE	**0.54**	**0.17**	**0.11**
MDE	**1.02**	**0.24**	**0.16**

Design response spectra of the dam

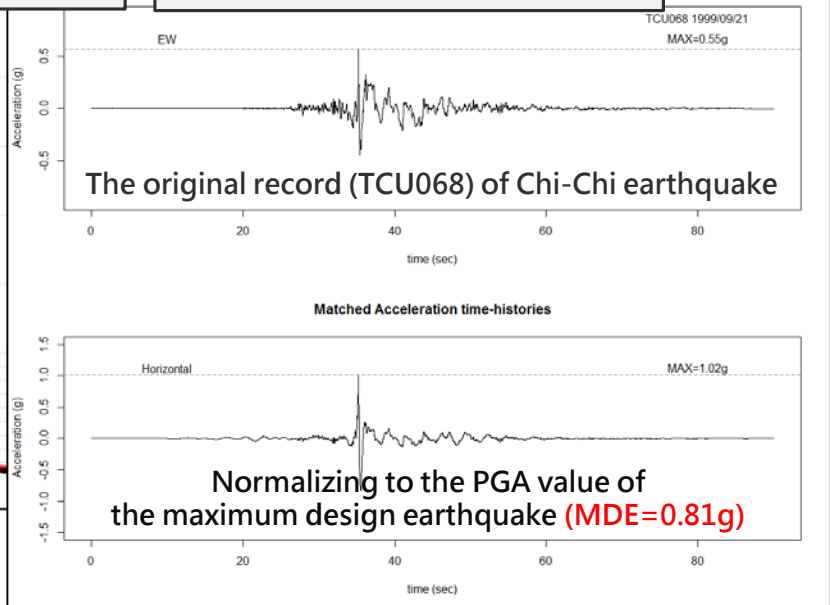
Design response spectrum for the Wushantou Reservoir



The goodness of fit of the design response spectrum and synthetic response spectrum



Original earthquake time series and synthetic time series



Dam Seismic Analysis and Strengthen

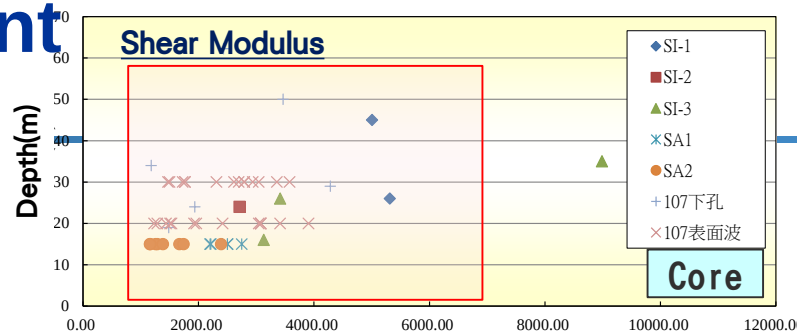
Assessment of Dam Improvement
- Construction Material

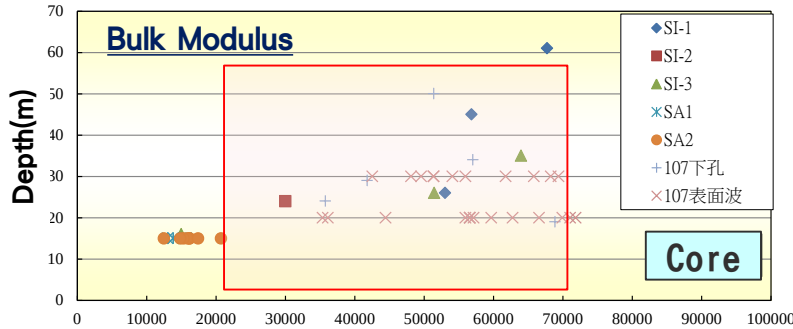
Parameters Reviewing

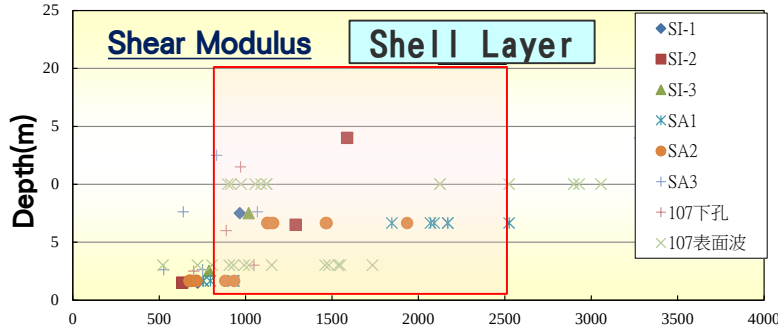
- Based on test results (in 1984,1989 and 1994), and non-destructive testing(NDT) results in this study.
- Shear modulus and bulk modulus of material (core and shell layer) show certain trend.
- Because drilling test is not carried out, adopted parameters for analysis refer to previous research.

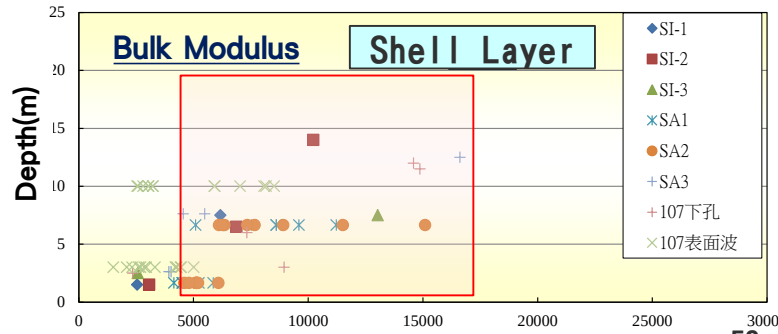
Parameters Table

	Core	Sandy layer	Gravel–cobble	Bedrock	Backfill	RC cut-off trench
Permeability Coefficient K_v (m/sec)	5.2×10^{-8}	2.2×10^{-6}	2.0×10^{-5}	1.9×10^{-8}	1.0×10^{-3}	1.0×10^{-10}
K_h/K_v	6	4	4	1	1	4
γ_t (T/m^2)	1.67	1.58	2.00	-	2.00	2.4
γ_{sat} (T/m^2)	2.00	2.00	2.02	2.70	2.02	2.4
C (T/m^2)	2.0	1.4	0.8	-	0.8	500
φ	29.3	35.8	37.5	-	37.5	-
Shear Modulus (kg/cm^2)	2,414	1,446	1,930	108,000	1,446	98,500
Bulk Modulus (kg/cm^2)	46,690	8,424	27,557	157,000	8,424	93,400
Poisson's ratio	0.315	0.267	0.254	0.220	0.25	-







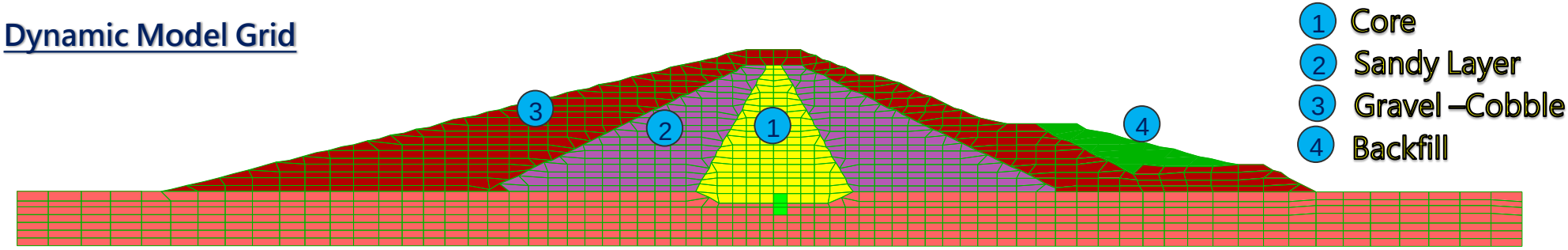


Sructural Stability and Stress Analysis-Dynamic Analysis

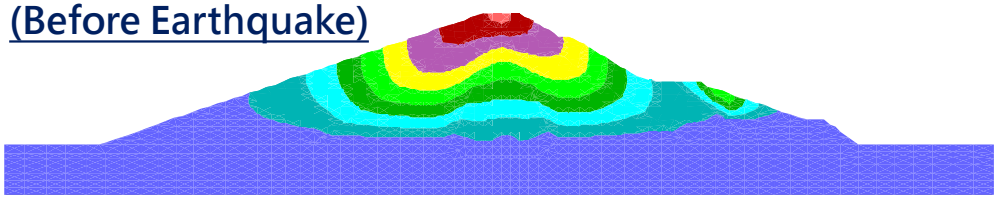
Dynamic Analysis Mode of Dam

- Length of dam (1,273m) / Height of dam (56.0m), ratio is 22.73, considered as shape of strip,deformation behavior is close to plane strain.
- Under design earthquake 0.81g, maximum deformation and settlement occur at maximum section. This study uses FLAC to simulate maximum section of dam, and conduct numerical analysis.

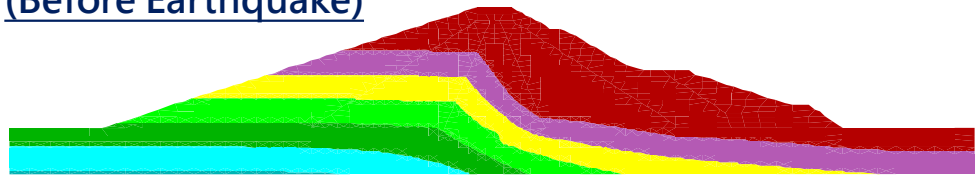
Dynamic Model Grid



Settlement
(Before Earthquake)



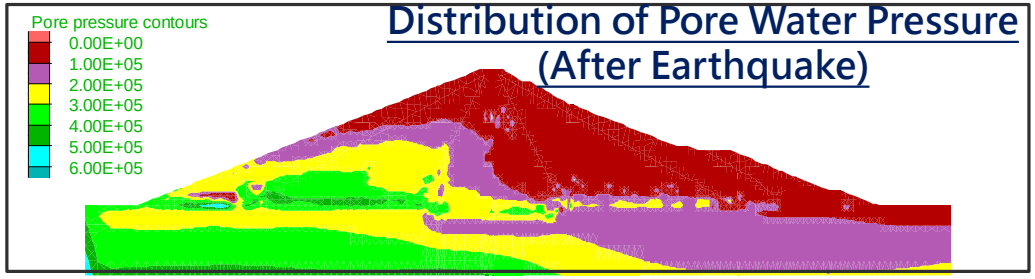
Distribution of Pore Water Pressure
(Before Earthquake)

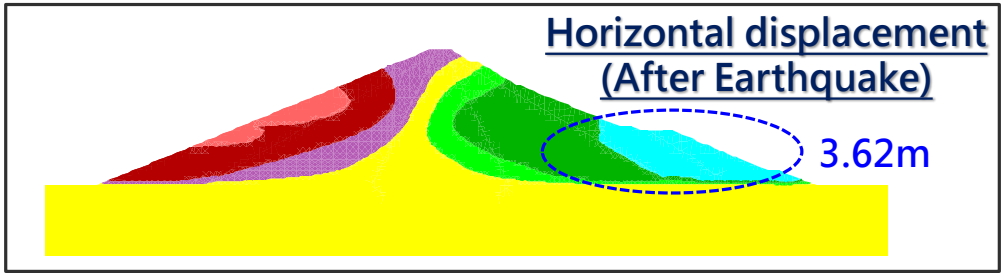


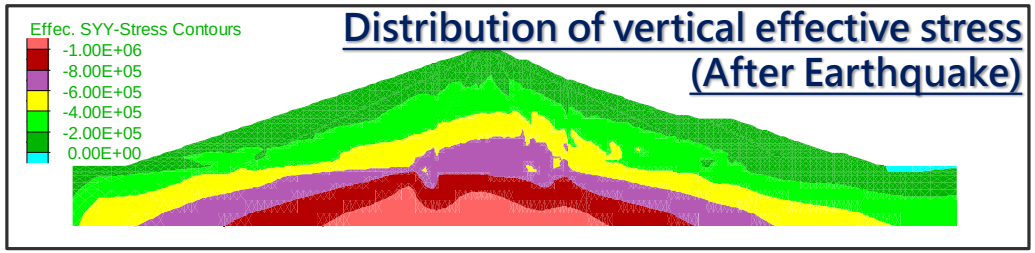
Sructural Stability and Stress Analysis-Dynamic Analysis

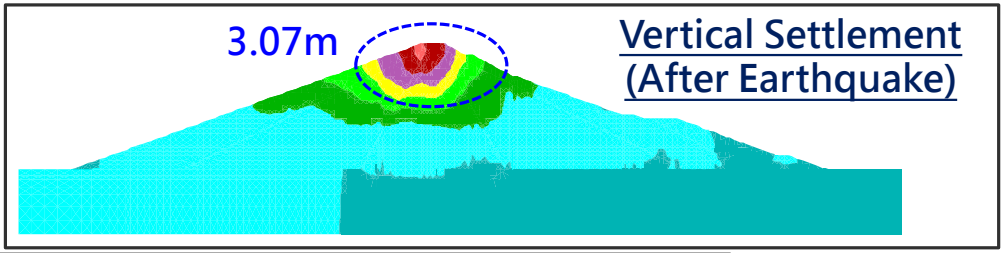
Result of Dynamic Analysis

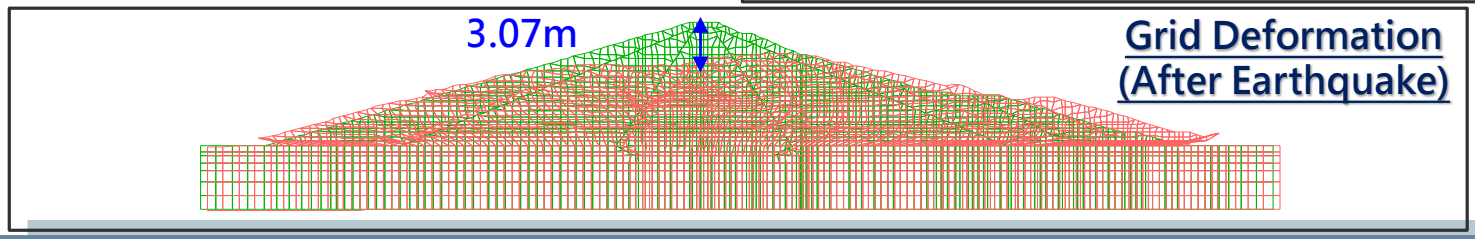
- Maximum settlement is 3.07m (top of dam); Maximum horizontal displacement is 3.62m (down-stream slope).
- Lost freeboard after earthquake is 3.0m, freeboard is still enough (Level of top of dam lower to EL.63.59m, and normal freeboard needed to reach is EL.61m)
- According to USA California's Norms (deformation over 3m), earthquake-resistant ability is insufficient, thus improvement is recommended.



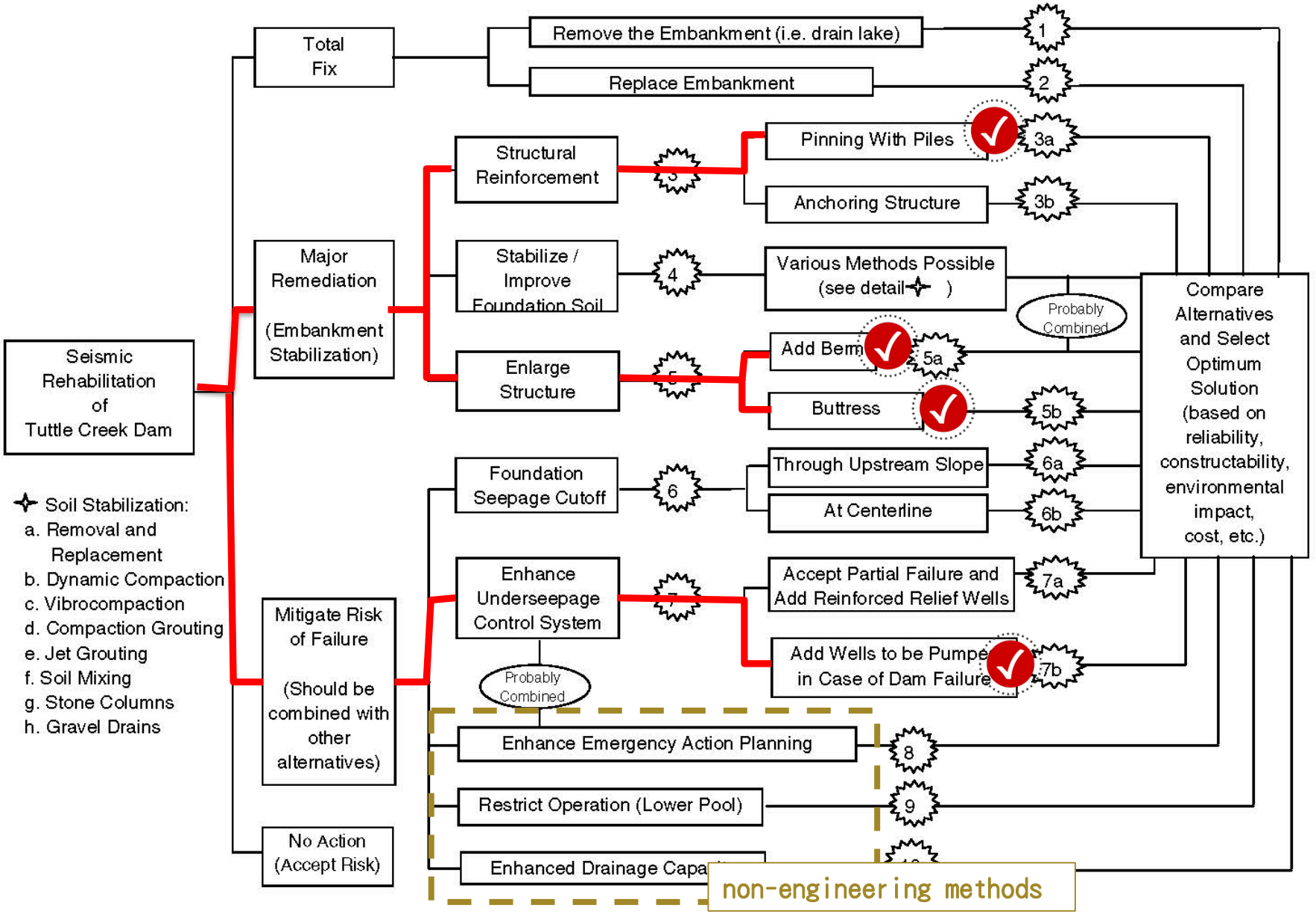








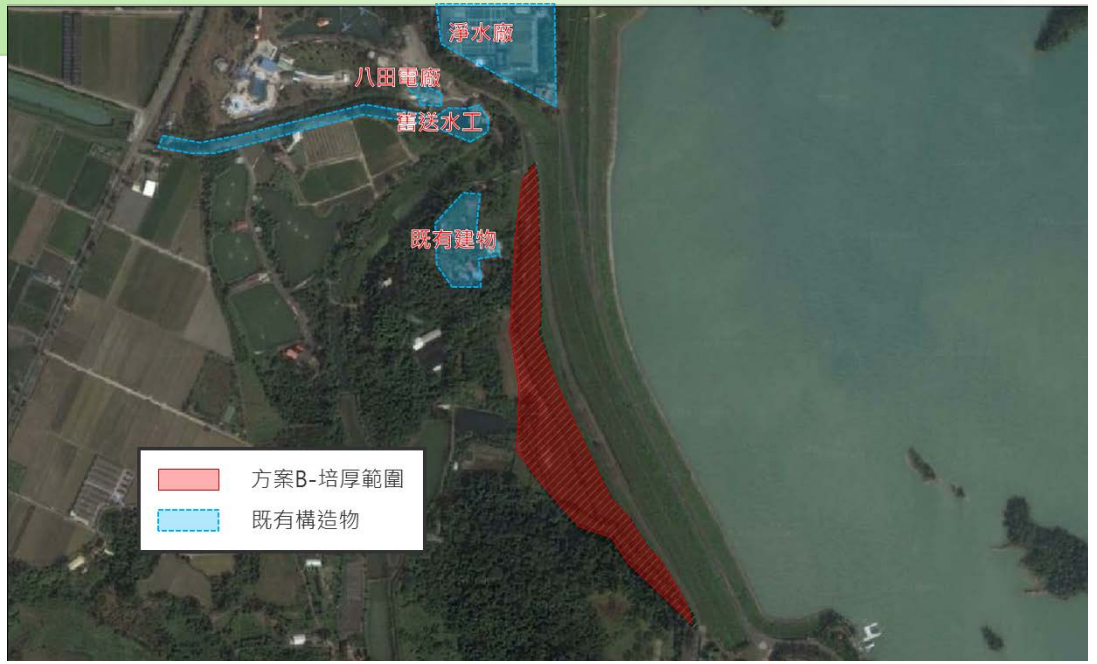
Dam Reinforcement - Literature Review

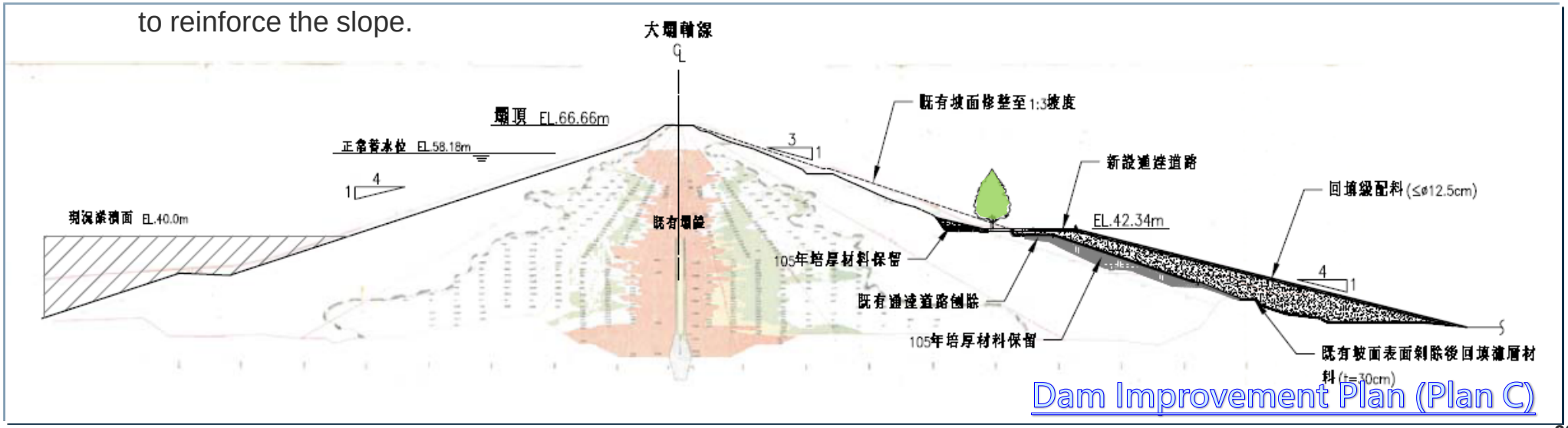


Dam Reinforcement Analysis -Reinforcement plan

Dam Improvement Plan

- Improvement methods: slow down the slope, weighting and strengthening slope toe with rocks
- Description ：
  - Local buttress and slope toe reinforcement
  - At the EL42.34 where the downstream slope was improved in 2016, the slope was buttress with a 1:4 gradient, followed by laying a filter layer, filling the river bed material, and then throwing stones (about 50cm) on the surface to reinforce the slope.



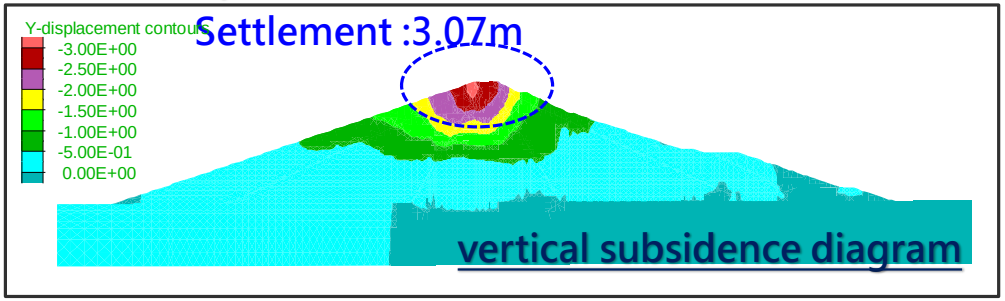


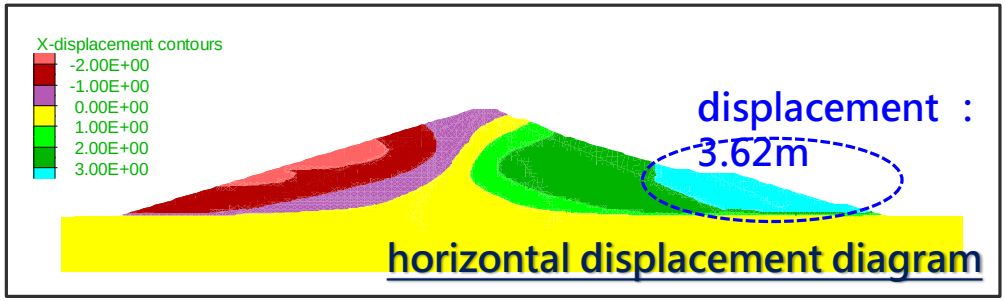
Dam Improvement Plan (Plan C)

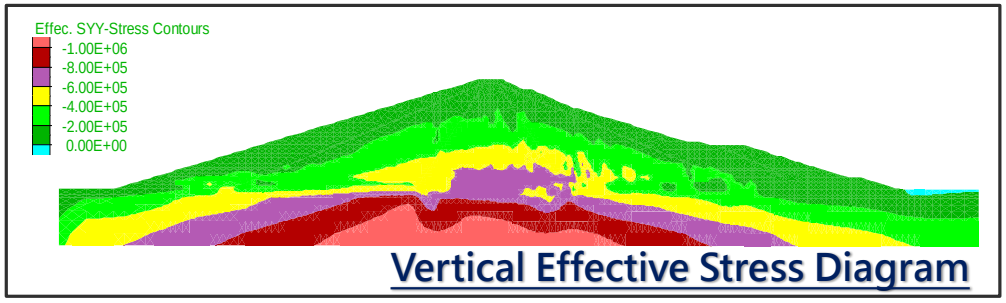
Dam Reinforcement Analysis -Feasibility Assessment

Dynamic Analysis (PGA=0.81g)

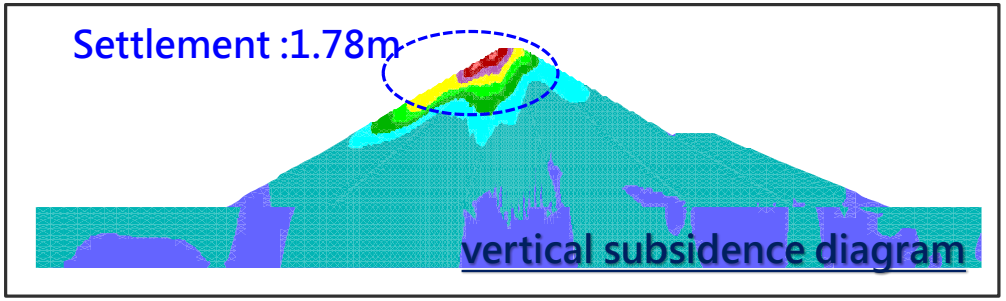
before improvement

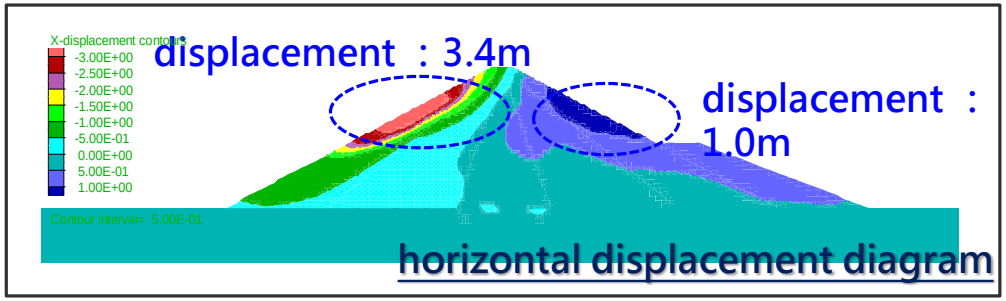


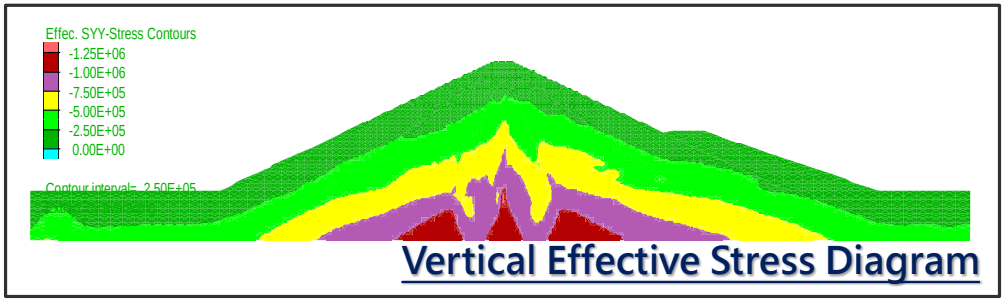




After improvement







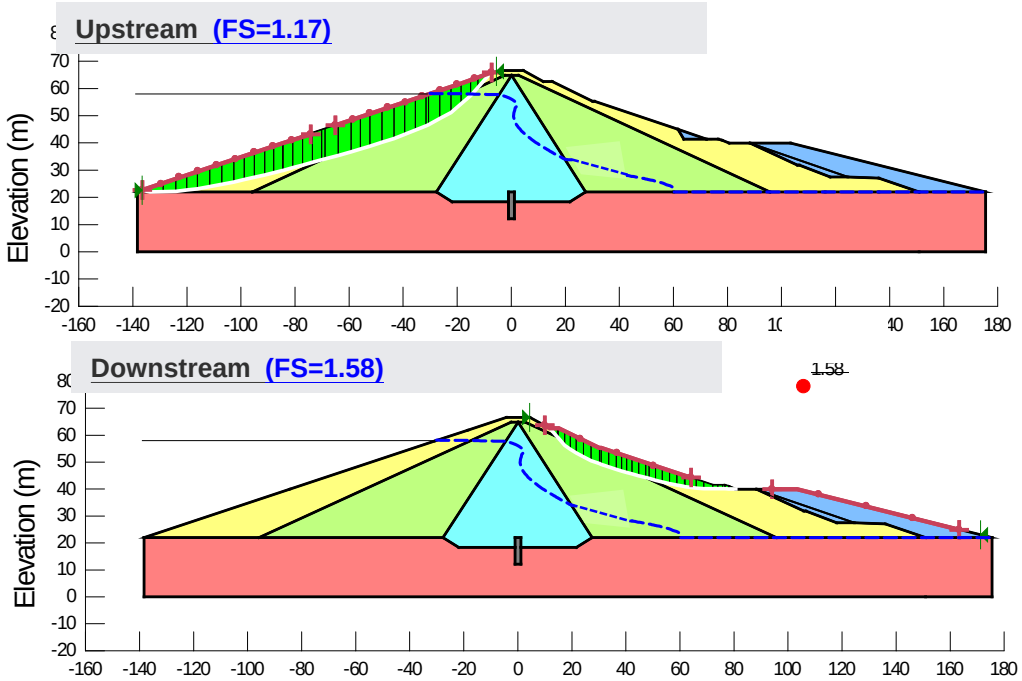
- The maximum subsidence is 1.78 m (upstream side of the dam crest); the maximum horizontal displacement is 3.40 m (upstream slope surface).
- After the earthquake, the lost water height was 1.78 m(EL.64.88m), which is enough(at least EL61m)

Dam Reinforcement Analysis –Feasibility Assessment

Stability Analysis

- 2D Finite Element Program： SLOPE/W
- Situation ：
  - stability analysis under steady seepage
  - stability analysis during sudden release
  - Stability Analysis when earthquake

- The upstream and downstream of the improved dam are safe in all conditions.

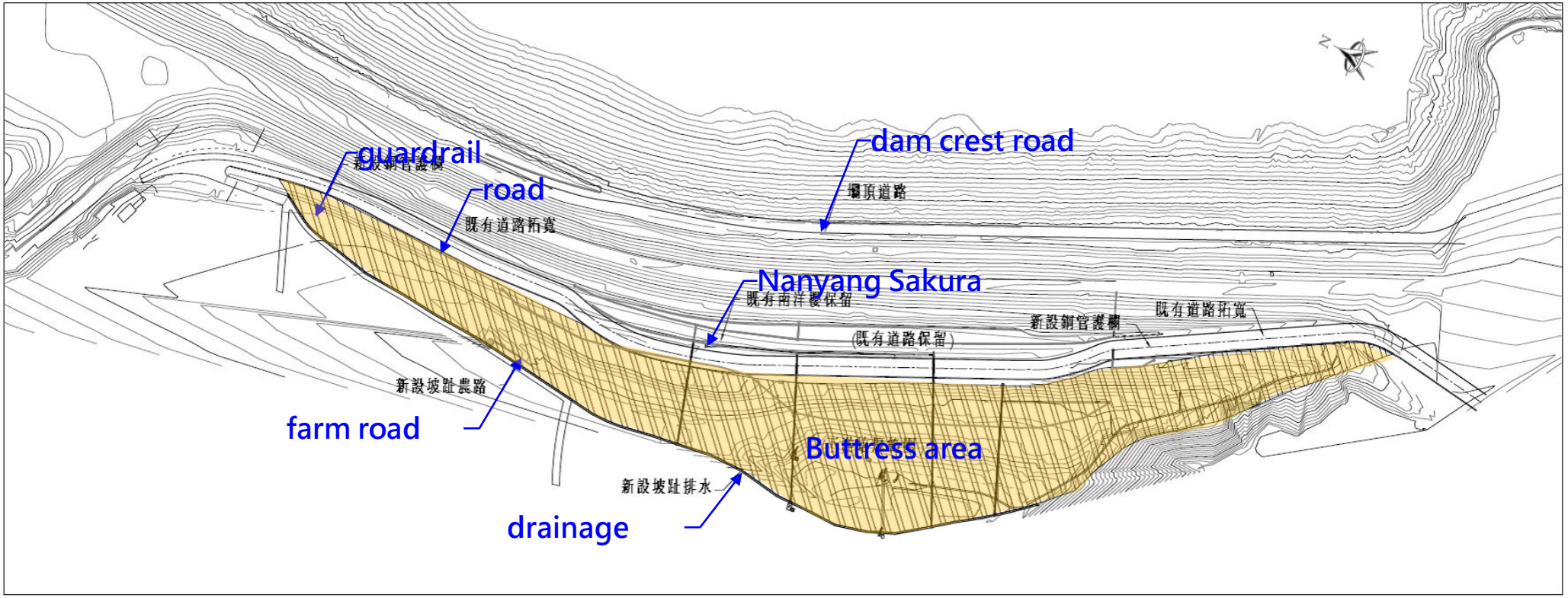


condition		upstream slope				downstream slope	
reservoir level		Steady seepage at full water level EL.58.18m		Emergency discharge to EL.40m (1/2 full water level)		Steady seepage at full water level EL.58.18m	
earthquake		NA	Kh=0.24	NA	Kh=0.24	NA	Kh=0.24
safety factor	Within 1/4 dam height		1.54		1.63		1.72
	Within 1/2 dam height		1.29		1.31		1.55
	Within 3/4 dam height		1.22		1.11		1.54
	full dam height	2.65	1.17	1.92	1.07	2.71	1.58
safety regulations		1.5	1.0	1.5	1.0	1.2	1.0

Engineering planning

- (1) Downstream slope buttress (2) Road engineering
- (3) Drainage system engineering(4) Monitoring system relocation project

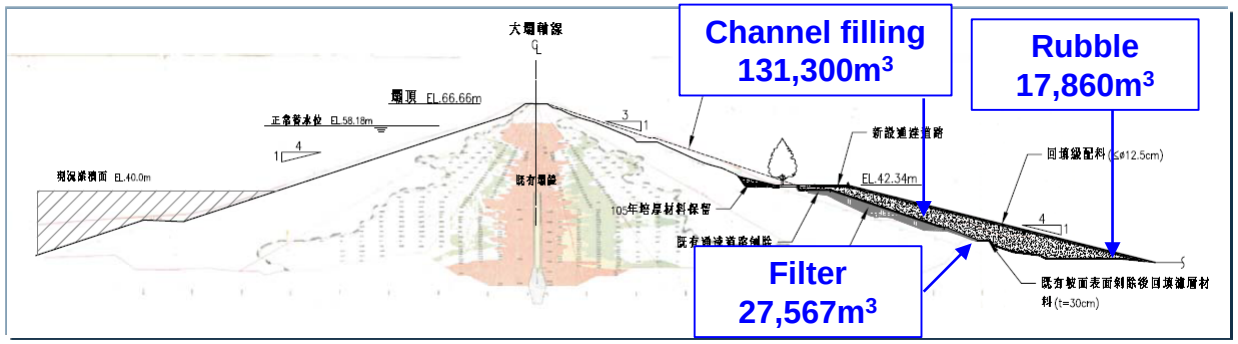
Downstream Slope Reinforcement



- The slope is 1:4 and thickened (about 10~15m), with an area of about 4.18 hectares. The construction sequence is to remove the surface soil (about 30cm) on the slope, and then lay the filter , river bed material and surface rubble in sequence (about 50cm).

Dam Reinforcement Analysis– Cost and Construction Period

Dam Improvement Plan (Plan C)



Estimated Construction Period

- New-built bem at downstream slope
- Total time of construction is 23 months
- Improvement of downstream slope is C.P.

項次	工作項目	月 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	下游坡面培厚工程																							
	1.1既有設施移除與整地																							
	1.2下游培厚																							
2	排水系統工程																							
3	道路工程																							
4	景觀工程																							
5	監測系統工程																							

Critical Path

Estimated Cost

項次	項 目 及 說 明	工程費(元)
壹	直接工程費	
(一)	主體工程	
1	下游坡面培厚工程	157,893,252
2	排水系統工程	4,750,000
3	道路工程	7,200,000
4	監測系統遷改工程	2,000,000
5	景觀工程	1,781,000
(二)	雜項工程	40,299,180
(三)	用地徵收費	1,926,400
	小計	215,849,832
貳	間接工程費	
1	勞工安全衛生費(約直接工程費之1.5%)	3,237,747
2	環境保護措施費(約直接工程費之1.5%)	3,237,747
3	廠商品質管制作業費(約直接工程費之2.0%)	4,316,997
4	工程綜合保險費(約直接工程費之1.2%)	18,192,663
5	包商管理費	22,105,990
6	工程預備費(約直接工程費之10%)	21,584,983
7	營業稅(5.0%)	14,426,298
	總計	302,952,258

- Estimated cost of plan C is 300 millions
- Water withdraw is not needed.
- Subsidies for land retirement is not needed.