路權外環境與地質因素對鐵道構造物的影響
Impact of Environmental and Geological Issues to HSR Infrastructure

Dr H.W. Yang
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Impact of Environmental and Geological Issues to HSR Infrastructure

- Education : Ph D, Civil Engineering Dept, UC Davis
- Experiences
  - Adjunct Professor NTU (CE, Railway Technology Research Center)
  - Taiwan High Speed Rail Corporation (1998 ~2023)
- Specialty
  - Civil-Track Interface Issues Identification and Analysis
  - Remedial Work Planning and Implementation to Rectify Track Irregularity
  - Ground Subsidence: Soil/Ground Water/Pile/Track Interaction
  - HSR Slope Precaution and Disaster Warning System
  - HSR Tunnel Safety
  - HSR Interface Management and System Integration

路權外環境與地質因素對鐵道構造物的影響
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1. Why Environmental and Geological Issues outside of ROW are critical to HSR Operation?
2. Case I : Ground Subsidence
3. Case II : Slope Safety
4. Conclusions

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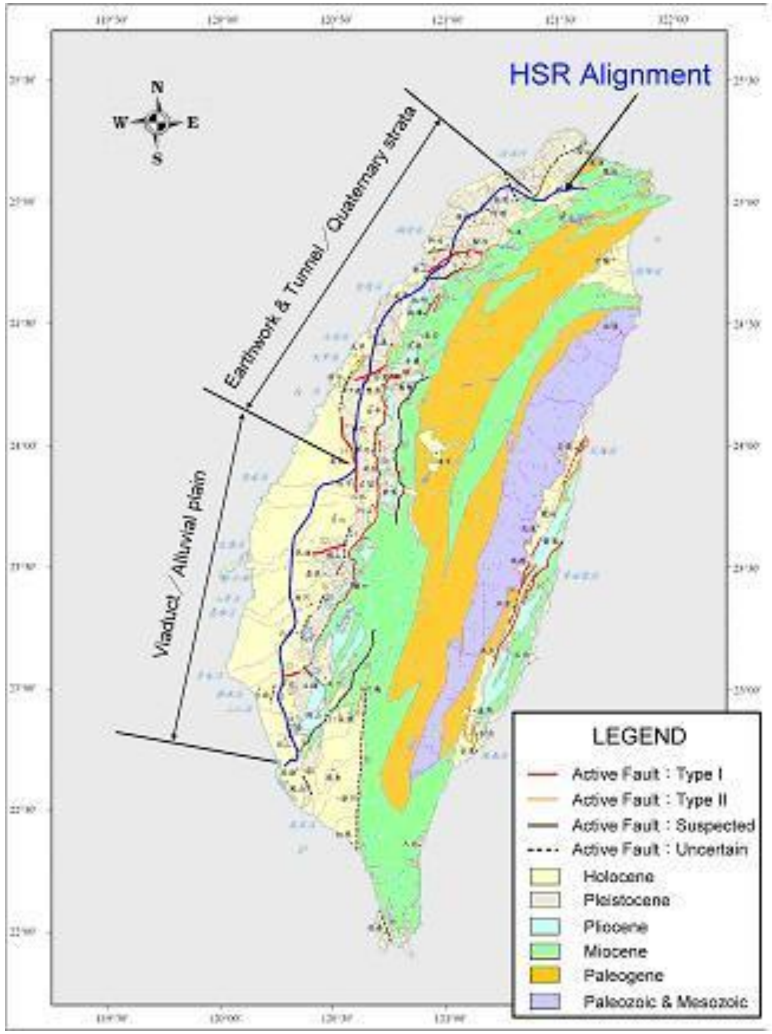


1. 345 KM
   - Bridge/viaduct : 242 KM (73%)
   - Tunnel: 48 KM(15%)
   - Cut/Fill: 40KM(12%)

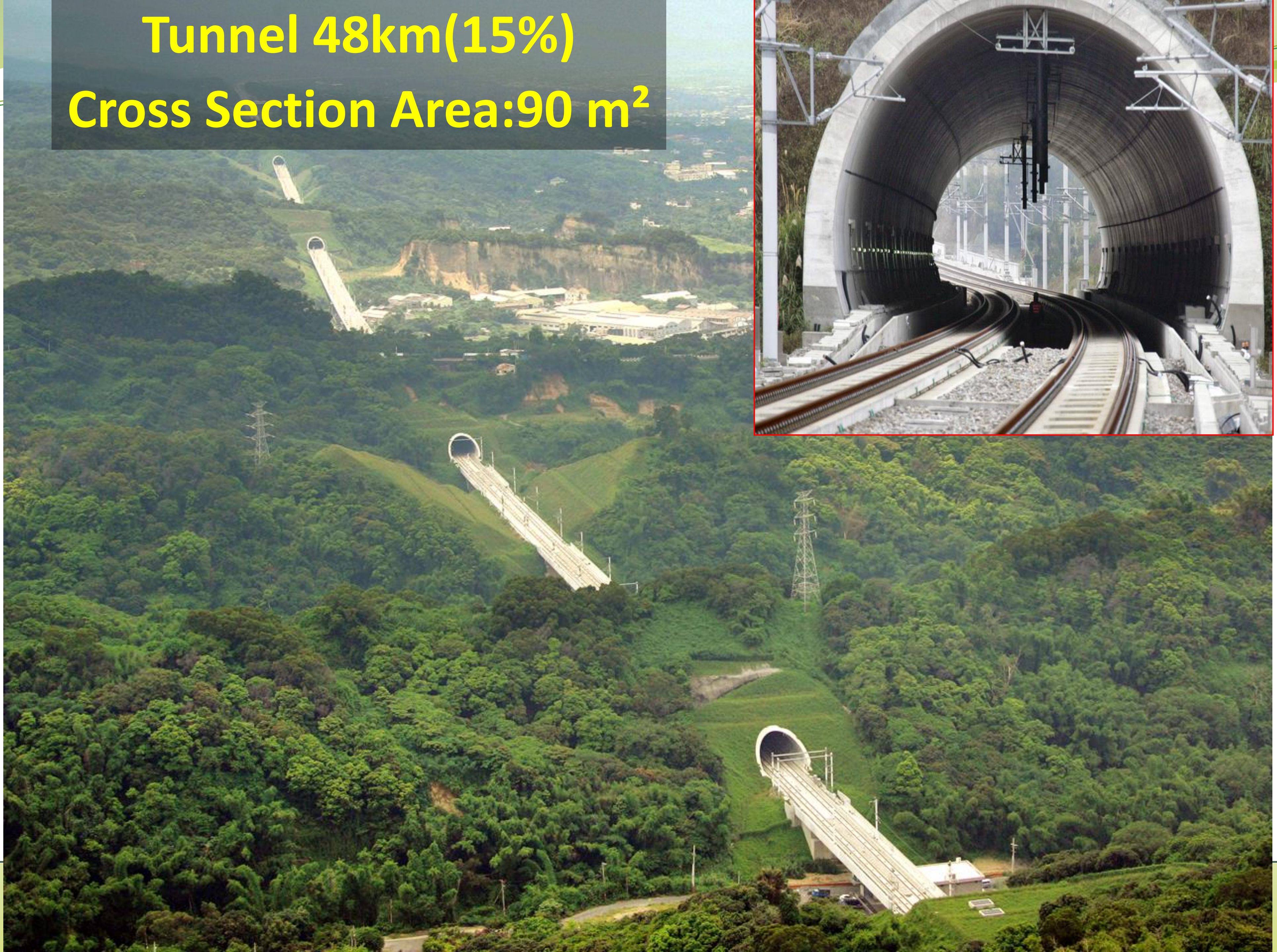
2. Took 6 years to build from 2000 to 2006

3. Services began on January 5, 2007

4. Crossing 26 rivers and 6 seismic active faults

Cut & Fill 40km(12%)

Tunnel 48km(15%)
Cross Section Area:90 m^2



Bridges & Viaducts 242km(73%)

路權外環境與地質因素對鐵道構造物的影響
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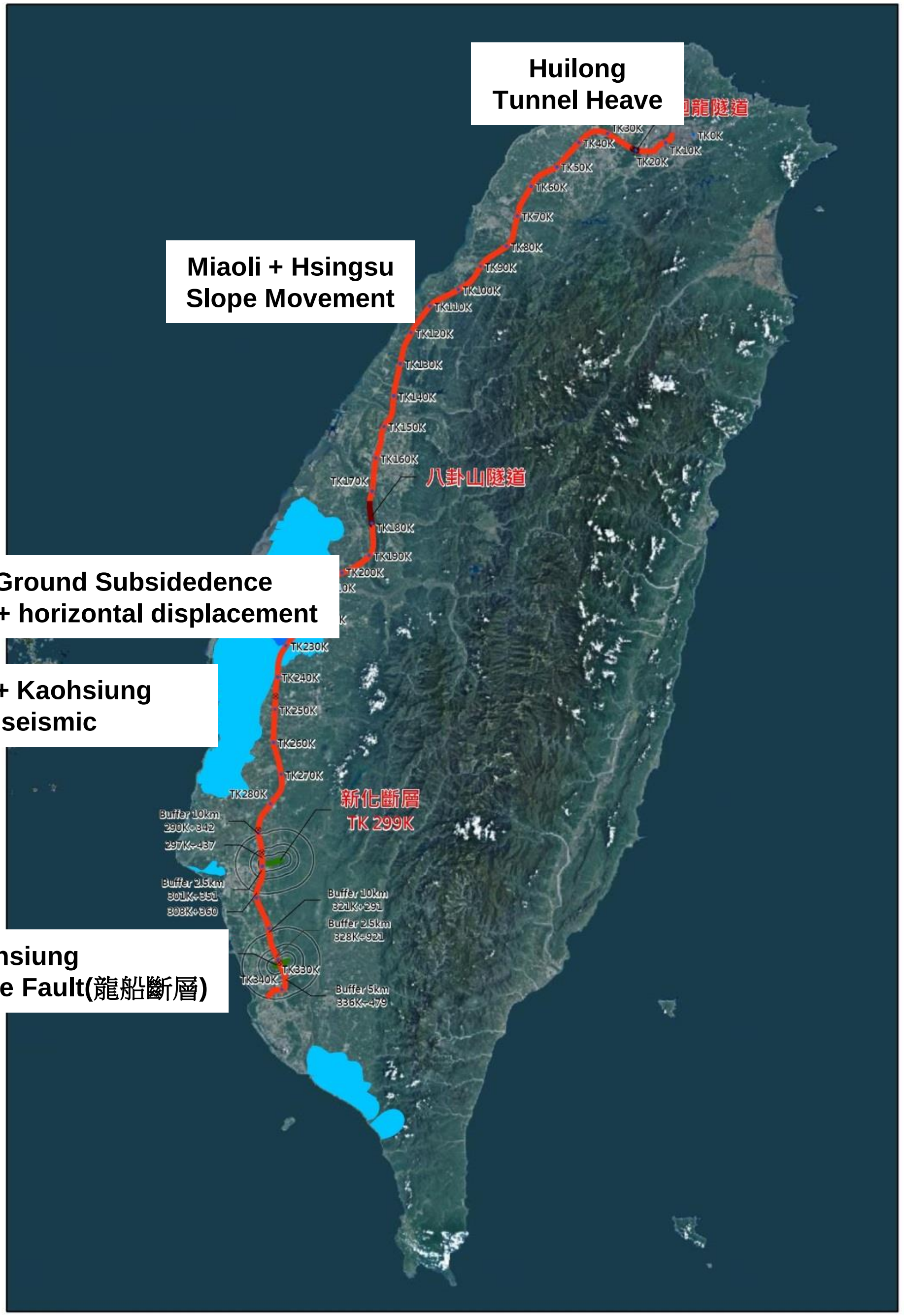
1. Heave : Huilong Tunnel (迴龍隧道)
2. Slope : Miaoli & Hsinhsu
3. Ground Subsidence + Horizontal Movement : Yunlin
4. Co-Seismic Displacement : Tainan + Kaohsiung
5. Creeping Fault : Kaohsing



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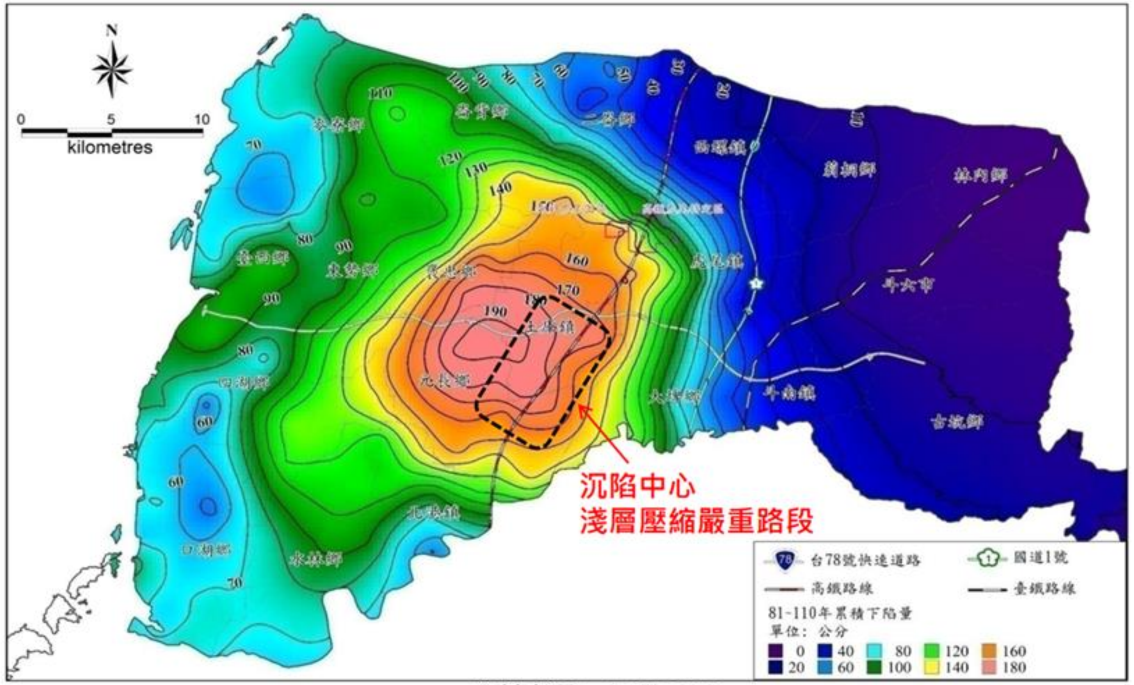

資料來源: 工研院2022

- For the given alignment, all the constructions were conducted within the right of way (ROW).
- Which party should be responsible for the impact from Environmental and Geological Issues originated from outside of ROW ?
  - Government?
  - Taiwan High Speed Rail Corporation?
  - Civil work contractor ?

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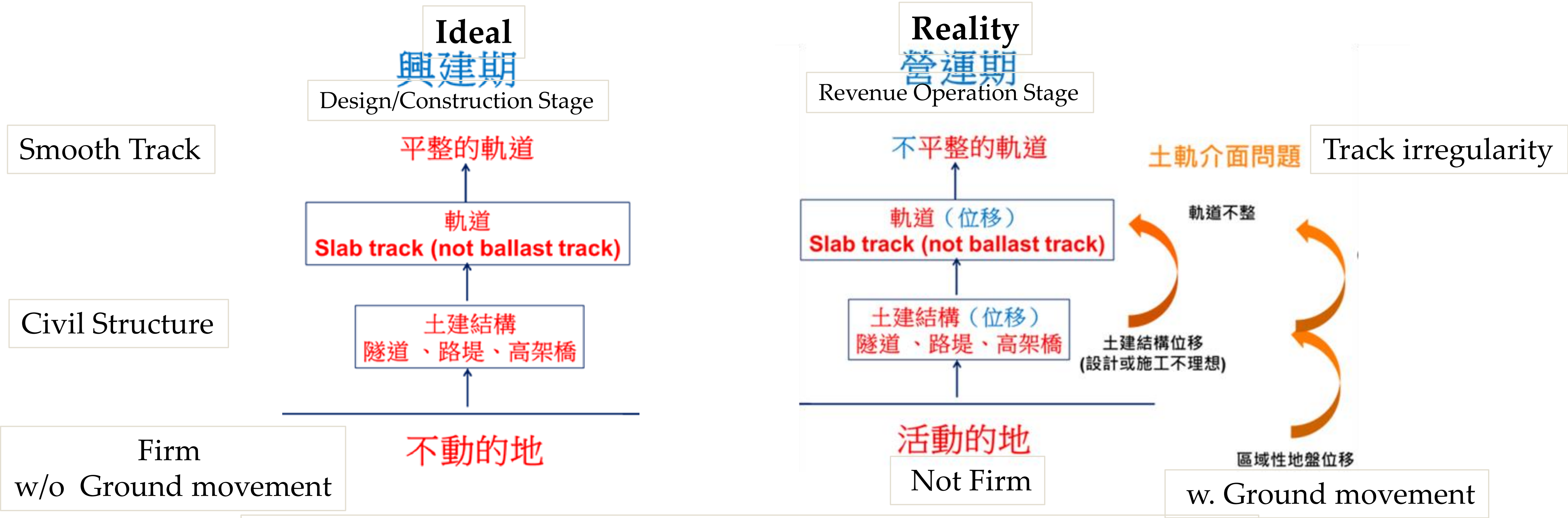

理想很豐滿，現實很骨感

Ideal is full, the reality is very skinny

路權外環境與地質因素對鐵道構造物的影響
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1. 鐵道系統與公路、高層建築的基礎最大的不同就是差異沉陷之限制要求較為嚴格。
   1. Comparing with other transportation infrastructures such as freeway and MRT, the geotechnical engineering design for high-speed rail project adopts similar principles but with more stringent allowable displacement of foundation structure.
2. 由於列車在軌道上運行，因此列車速度越快，對軌道平順度要求越高，相對的對道床結構的穩固性要求也越高。道床結構的不穩固會導至軌道幾何狀況不平順。
   1. The higher operational speed, the higher standard for track regularity
3. 軌道平順是地工結構物滿足服務性的目標。
   1. The serviceability of foundation is to ensure the track regularity fulfill the requirement for safety and comfortability.
4. 高鐵土建設計準以角變量（angular displacement）做為指標
   1) 高架橋簡支梁 (simple support bridge) : < 1/1000
   2) 高架橋連續梁(continuous structure): < 1/1500
   3) 路工段與隧道(tunnel and embankment) : < 10mm/20m

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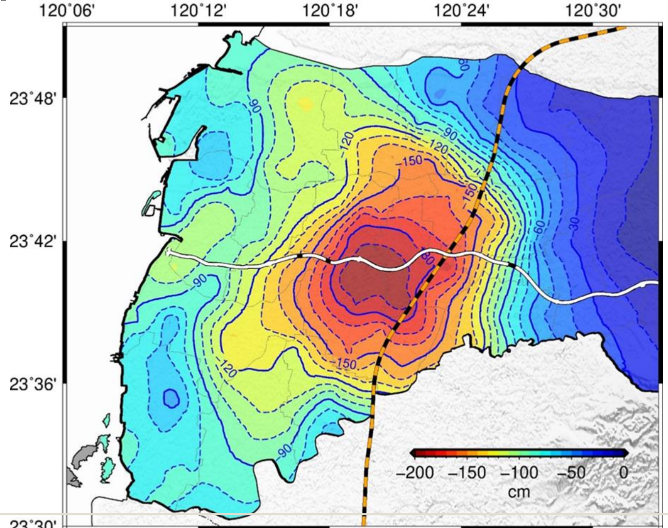
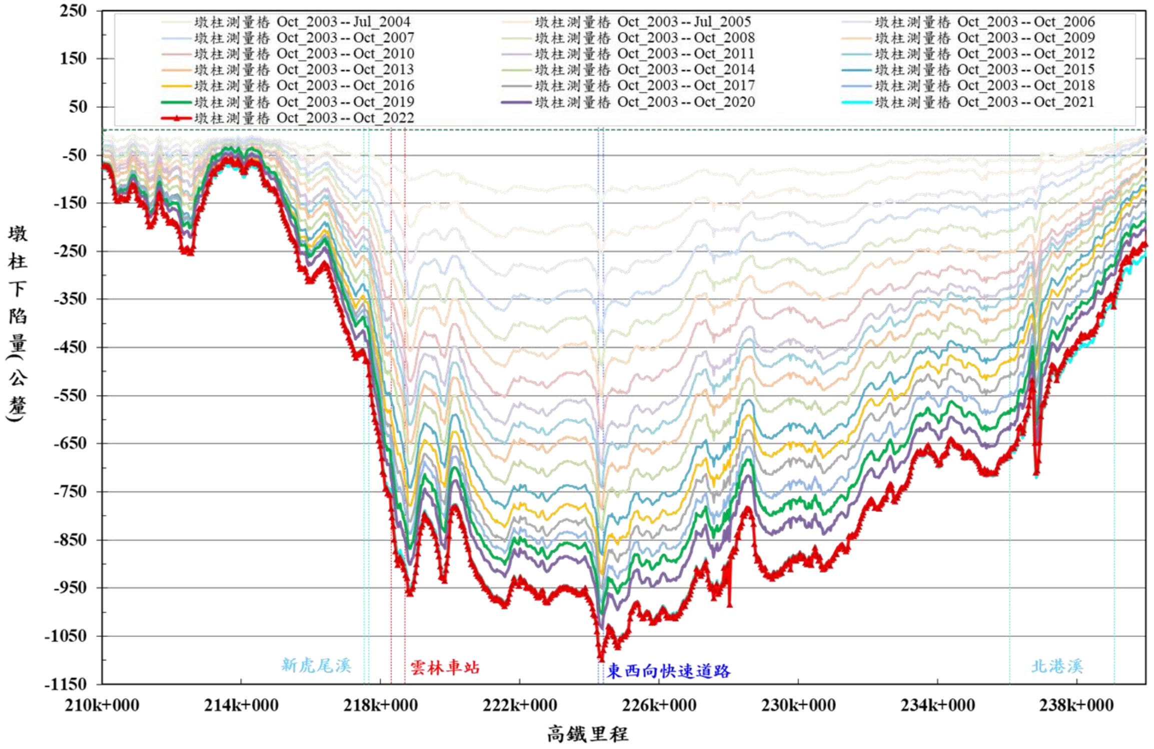
Ground Subsidence(案例一, 地層下陷)

1. Over-exploitation of ground water is the main cause.
   1) Since early 1950, mainly along the four townships in west coast area for aquaculture .
   2) We first observed the ground subsidence in 2000 along the HSR alignment. Up to 2022, the max. accumulate HSR structure settlement is around 2m.



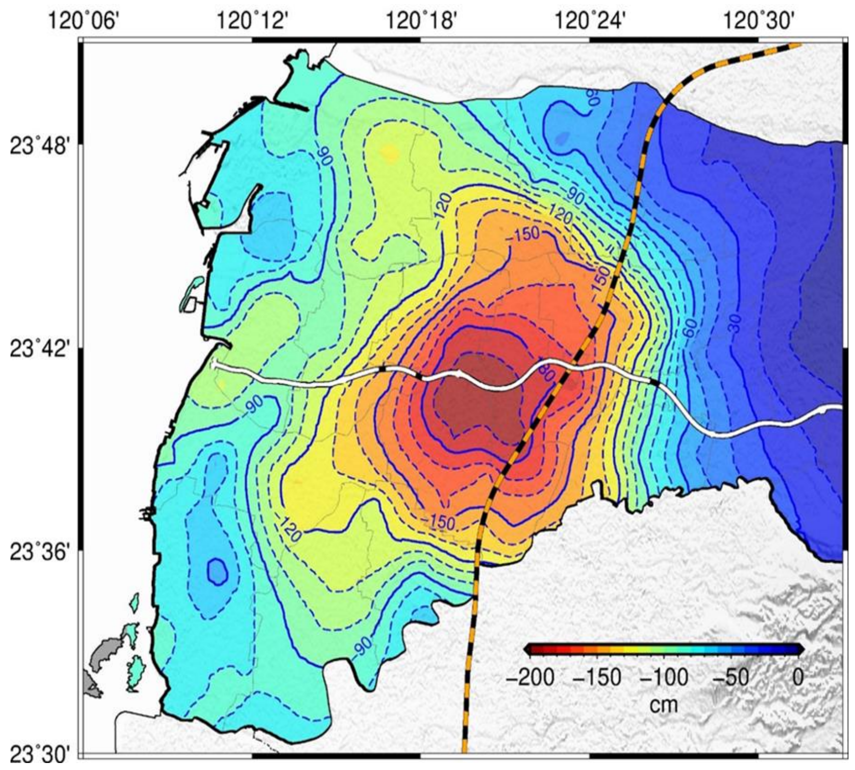
1992~2022年雲林地區累積下陷量圖



2003年10月~2022年10月高鐵沿線累積下陷量圖

路權外環境與地質因素對鐵道構造物的影響
Impact of Environmental and Geological Issues to HSR Infrastructure
Ground Subsidence(案例一, 地層下陷)

1. Major Concerns from Governmental Authority
    1) Under the same management /control regulation, why the ground subsidence in Yunlin is much severe than in Chunghwa?
    2) To minimize the negative impact to HSR safety, the objective of ground water control & management is set at the level of 4 cm/year
2. How to enhance the R&D effort made by Governmental Authority



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路權外環境與地質因素對鐵道構造物的影響
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To minimize the negative impact to HSR safety, the objective of ground water control & management is set at the level of 4 cm/year

- Ground settlement 4 cm/year : there is no basis !
- Referring to the data in last 20 years， this goal is not reachable!
- Instead of specifying a number for this goal, it would be practical
  - first identifying the weak point of HSR structure suffering the negative impact from ground subsidence.
  - Then formulating the remedial work strategy.

Risk Elimination - 2 Stage Preventive Maintenance Work
Long Term Solution : removal of 92000 tons of earth

2003/01~2014/03 2014/03~2014/05

Ground water fluctuation and surcharge loading combined effect

路權外環境與地質因素對鐵道構造物的影響
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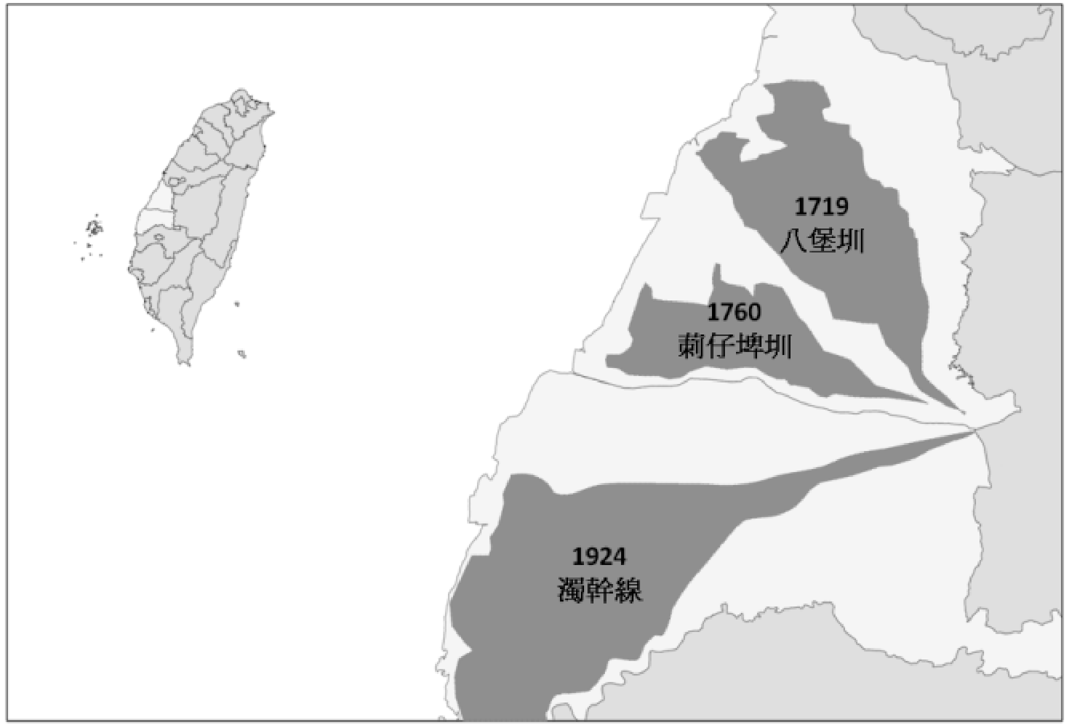
Under the same management /control regulation, why the ground subsidence in Yunlin is much severe than in Chunghwa?

- 施世榜是施琅的族侄，為清代臺灣重大水利工程八堡圳的創建者，從八堡圳(1709~1719)灌溉面積幾近 12,000 甲。
- 施厝圳引濁水溪灌溉，完工之後濁水溪南岸、北岸的景況從此南轅北轍；北岸的彰化平原一躍成為臺灣最富庶的地區，南岸的雲林地區則長期發展停滯。
- 雲林地區地面水源不足，仰賴地下水



圖三 濁水溪主要水圳的灌溉區

Ref: 濁水溪的歷史難題 ，張素玢(民國一ＯＯ年十二月 中央研究院臺灣史研究所)

路權外環境與地質因素對鐵道構造物的影響
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Ground Subsidence(案例一, 地層下陷)

Four Types of HSR Structure Settlement in Ground Subsidence Area

1. Type I：No ground surcharge loading，subject to the effect of deep pumping: (south of Zhuoshui River, Huwei)
2. Type II：No ground surcharge loading，subject to the effect of shallow pumping: (Tuku)
3. Type III：combined effect of surcharge loading and shallow pumping(Yunlin station、Tuku)
4. Type IV：horizontal movement(Three subsidence centers in Tuku, Huwei, and Xizhou)

Note: shallow means pumping depth within pile length area, roughly 70 meters below ground surface.

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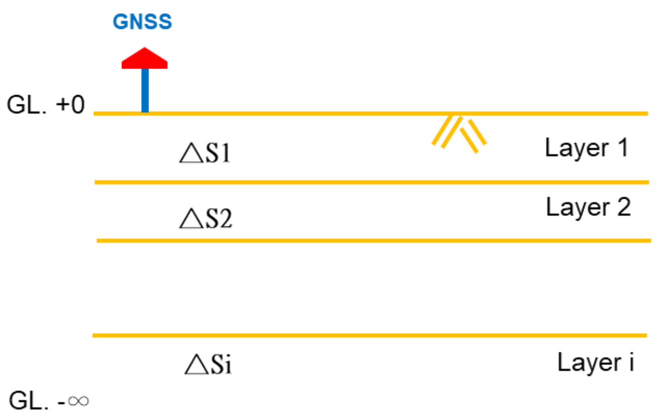
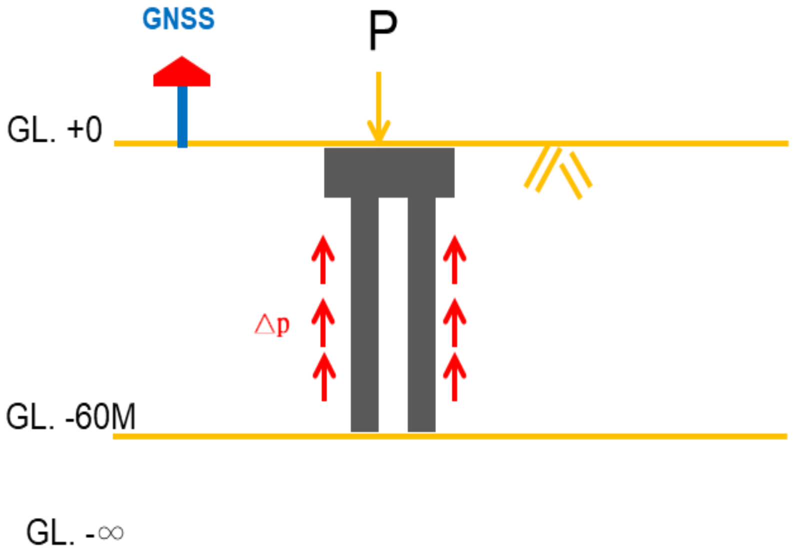
Ground Subsidence(案例一, 地層下陷)

Type I：No ground surcharge loading，subject to the effect of deep pumping
HSR structure loading < pile capacity (safety factor 1.5)
HSR structure sinks with the ground



地面沉陷量 = GNSS 沉陷量 = $\Sigma \triangle S$



If $\Sigma\triangle p > P$ (基樁承載力 >橋梁載重)

橋梁荷重 < 基樁承載力 (安全係數1.5)
橋墩沉陷與大地同步

橋墩沉陷量 = 地表下60M以下土層壓縮量的總和
= $\Sigma \triangle S$ (GL. -60 ~ ∞)
= GNSS - $\triangle S$ (GL.+0~-60M)

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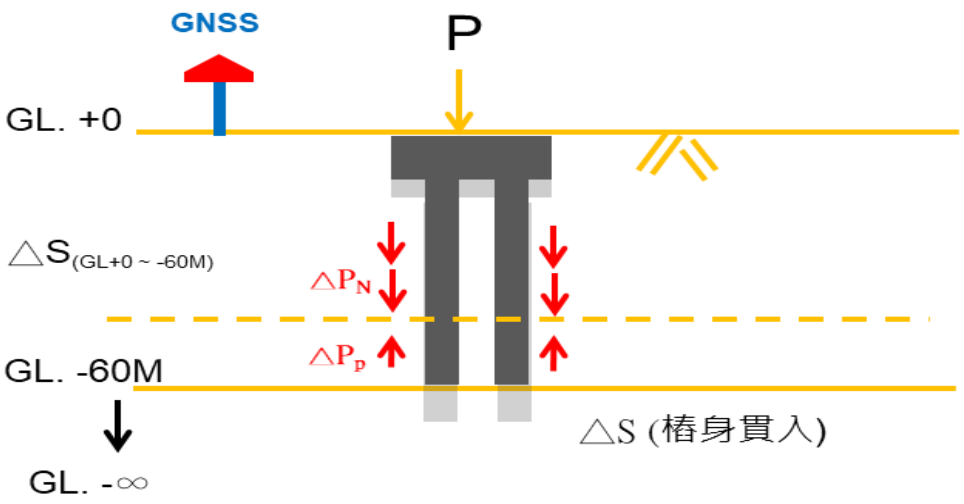
Type II：No ground surcharge loading，subject to the effect of shallow pumping

1. Pile capacity may be less than the design loading due to negative skin friction caused by compression of soil stratum adjacent to pile body
2. HSR structure sinks may higher than ground



If $(\Sigma\triangle P_N + P) > \Sigma\triangle P_p$ (基樁承載力 < (橋梁載重 +基樁負摩擦力)

橋墩沉陷量 = 地表下60M以下土層壓縮量的總和 + △S (樁身貫入)
= GNSS - $\triangle S_{(GL+0 \sim -60M)}$ + △S (樁身貫入)

淺層抽水造成土層壓縮，與樁身之相對位移造成基樁負摩擦力

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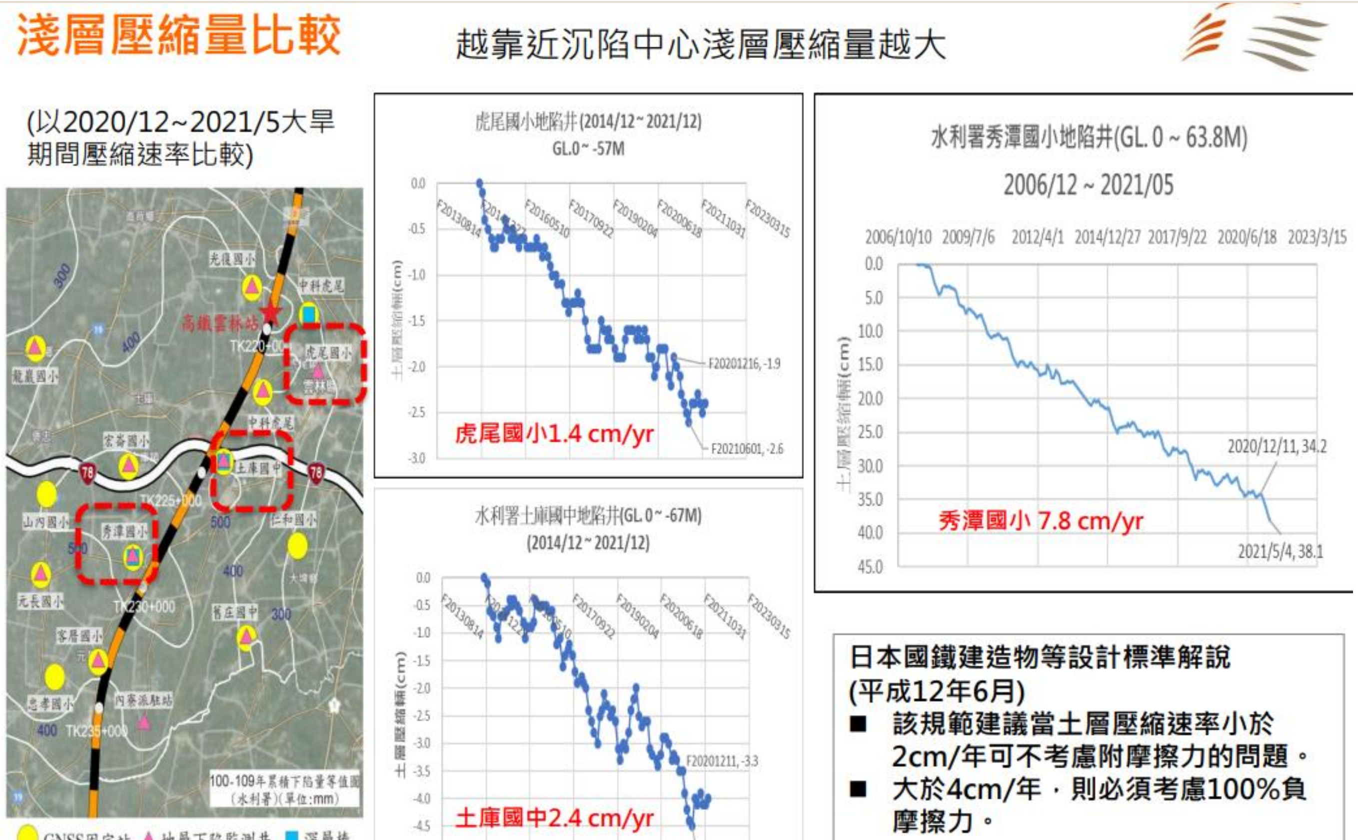
The difference between Type I and Type II：compression rate

1. Huwei : 1.4 cm/year, suffering no pile negative skin friction
2. Tuko :2.4 cm/year , suffering no pile negative skin friction
3. ST : 7.8 cm/yr , suffering full pile negative skin friction



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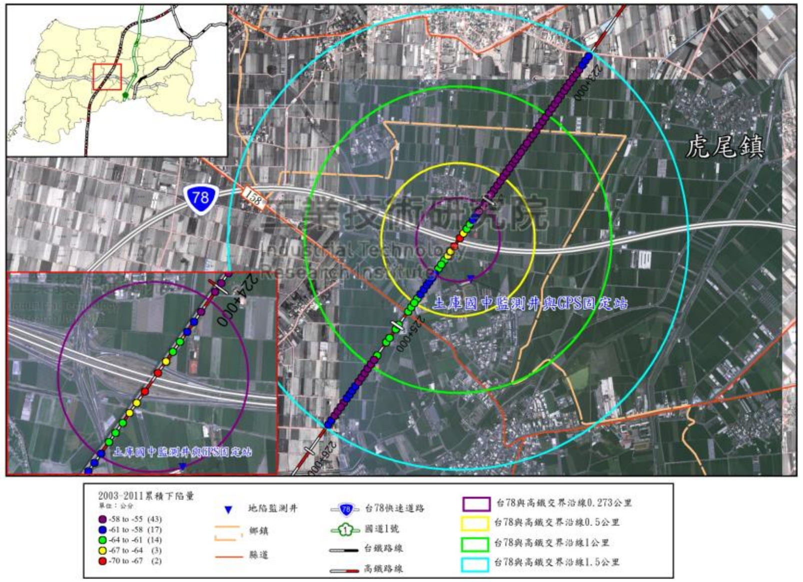
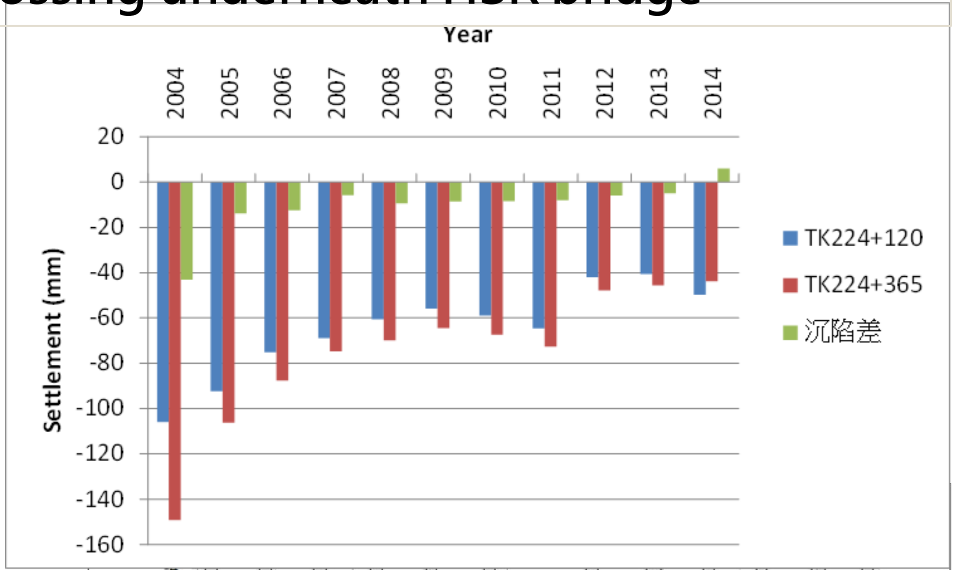
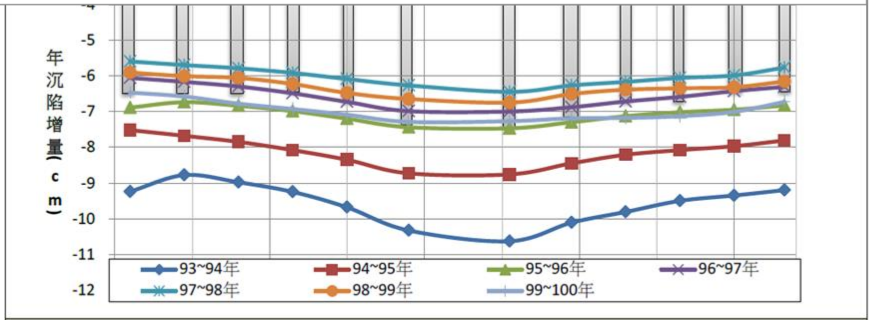
Ground Subsidence(案例一, 地層下陷)

Type III：combined effect of surcharge loading and shallow pumping
1. Extra settlement may last forever due to seasonal ground water fluctuation
2. Typical example :　No 78 express-way crossing underneath HSR bridge







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Ground Subsidence(案例一, 地層下陷)

Type III：combined effect of surcharge loading and shallow pumping
1. Extra settlement may last forever due to seasonal ground water fluctuation
2. Typical example :   No 78 express-way crossing underneath HSR bridge
3. Embankment of No.78 Express-way was removed in 2014

2003/01~2014/03

2014/03~2014/05

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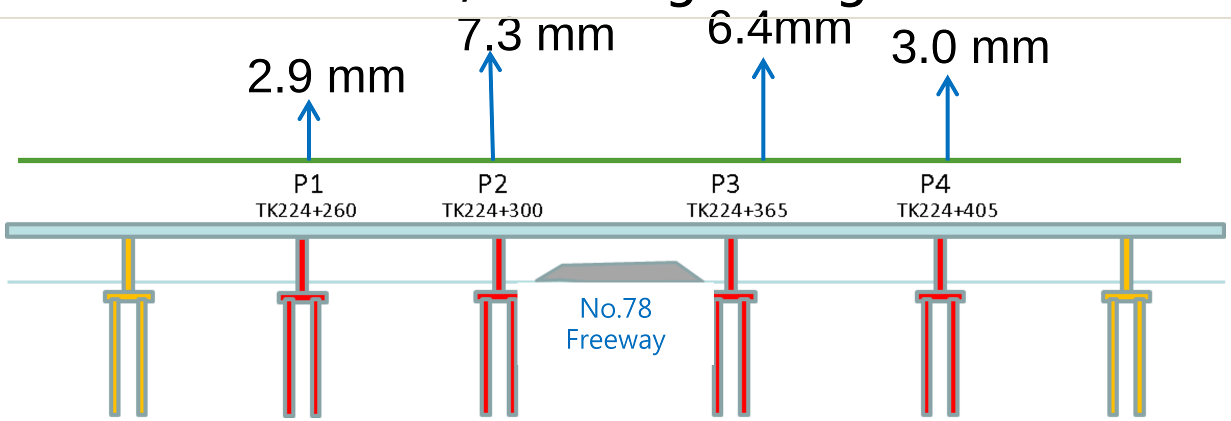
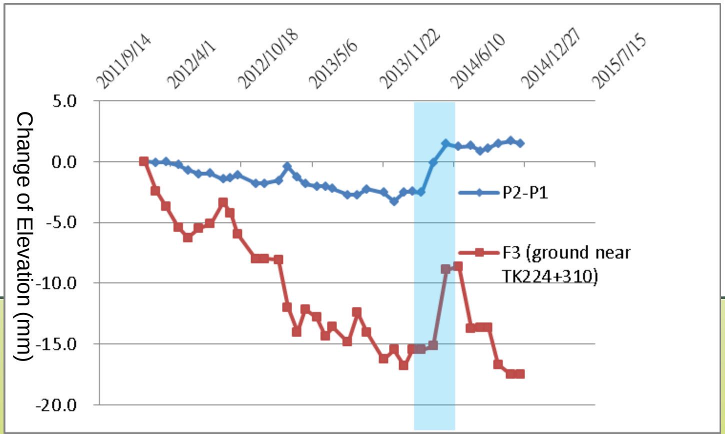
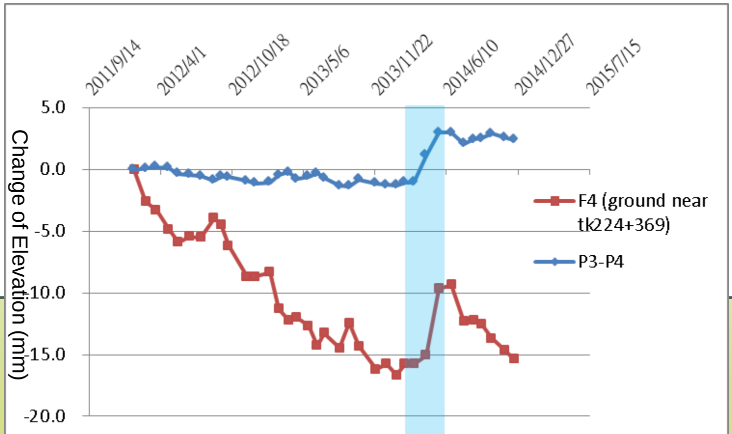
Ground Subsidence(案例一, 地層下陷)

Type III：combined effect of surcharge loading and shallow pumping

1. Extra settlement may last forever due to seasonal ground water fluctuation
2. Typical example : No 78 express-way crossing underneath HSR bridge
3. After removal of the embankment, the bridge and ground rebounded immediately.







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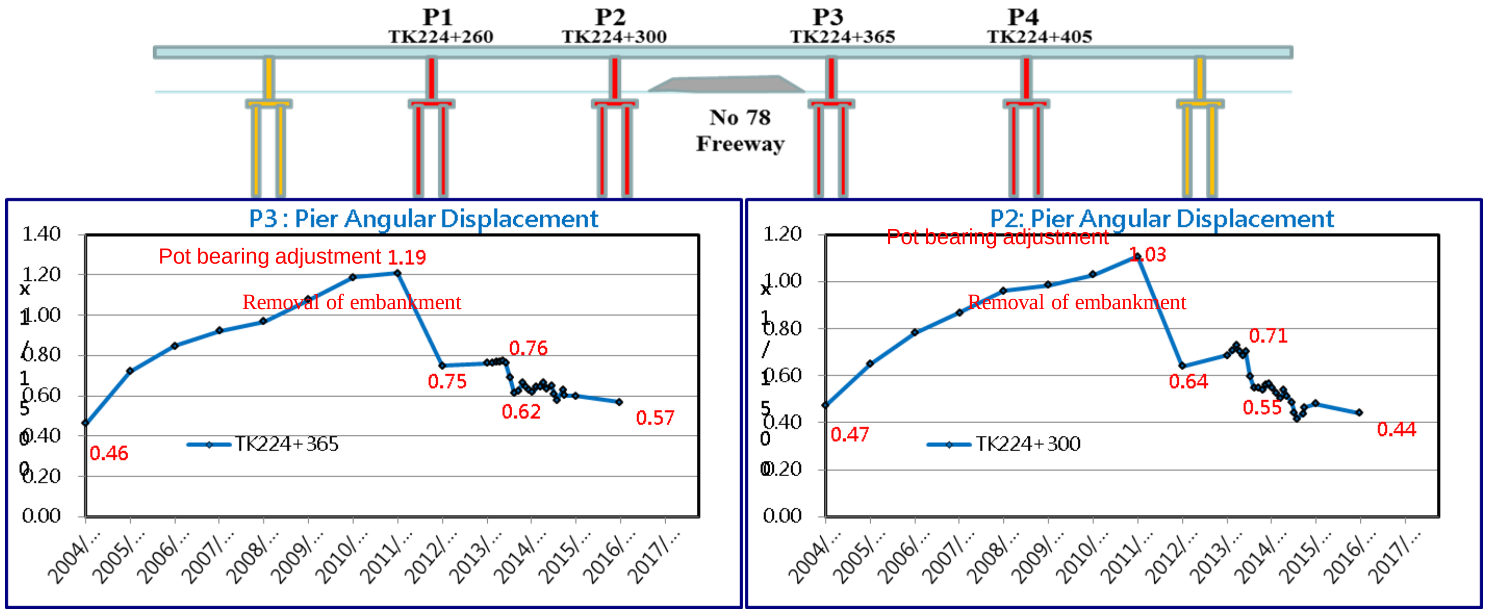
Type III：combined effect of surcharge loading and shallow pumping

1. Extra settlement may last forever due to seasonal ground water fluctuation
2. Typical example :   No 78 express-way crossing underneath HSR bridge
3. After removal of the embankment, the angular displacement between piers remains below the design level 1/15000

1. 2004~2011
   0.46/1500 => 1.03/1500
2. 2011 : pot bearing adjustment (THSRC)
   1.03/1500 => 0.64/1500
3. 2014 : Removal of embankment (Transportation Authority)
   0.71/1500 => 0.55/1500
4. 2017 : 0.44/1500



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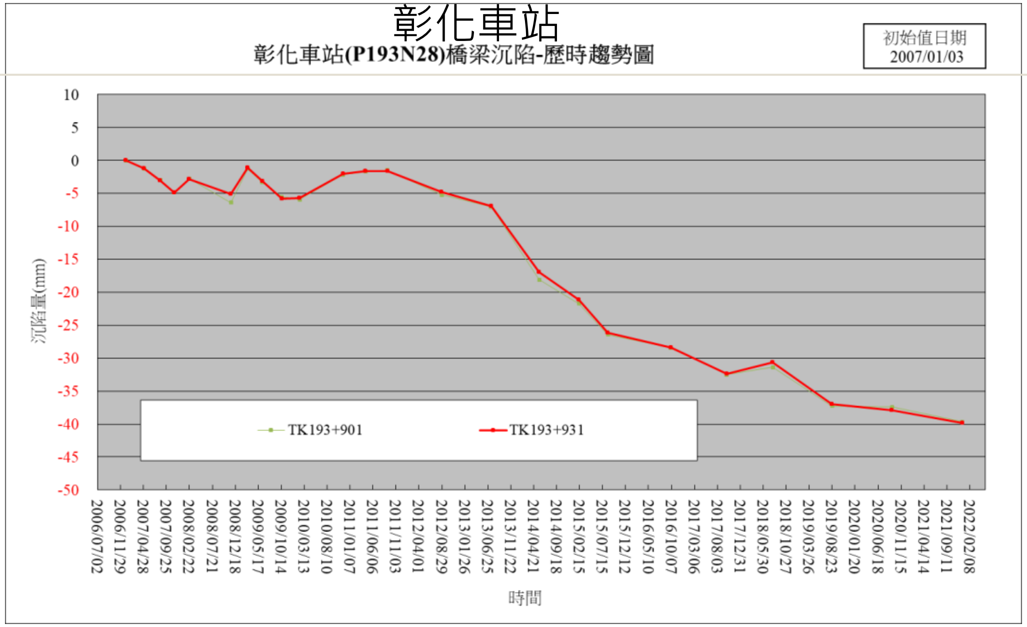
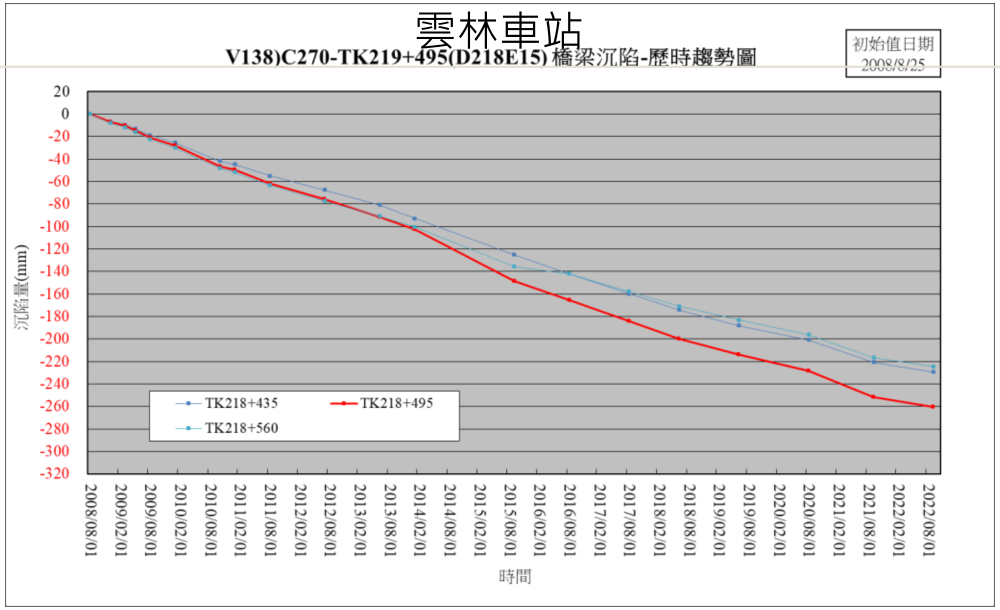
Impact of Environmental and Geological Issues to HSR Infrastructure
Ground Subsidence(案例一, 地層下陷)

Type III：combined effect of surcharge loading and shallow pumping

1. Extra settlement may last forever due to seasonal ground water fluctuation
2. HSR Yunlin station (with combined effect) vs HSR Chunghwa station (w/o combined effect)
3. The settlement of HSR Chunghwa station stabilized at 4 cm in 2018, however, the settlement of Yunlin station continues increases up to 26 cm in 2022.





彰化 : 雲林 = 4 cm : 26 cm

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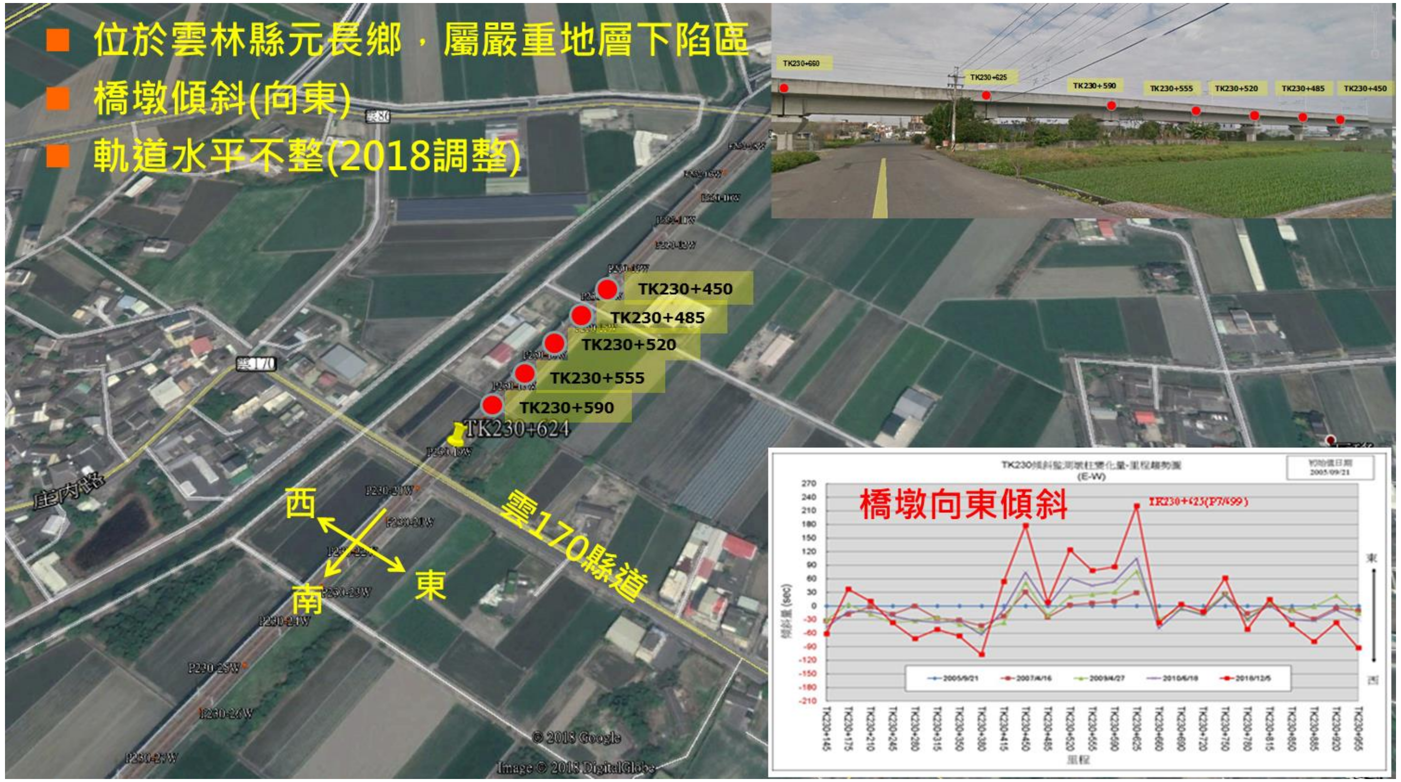

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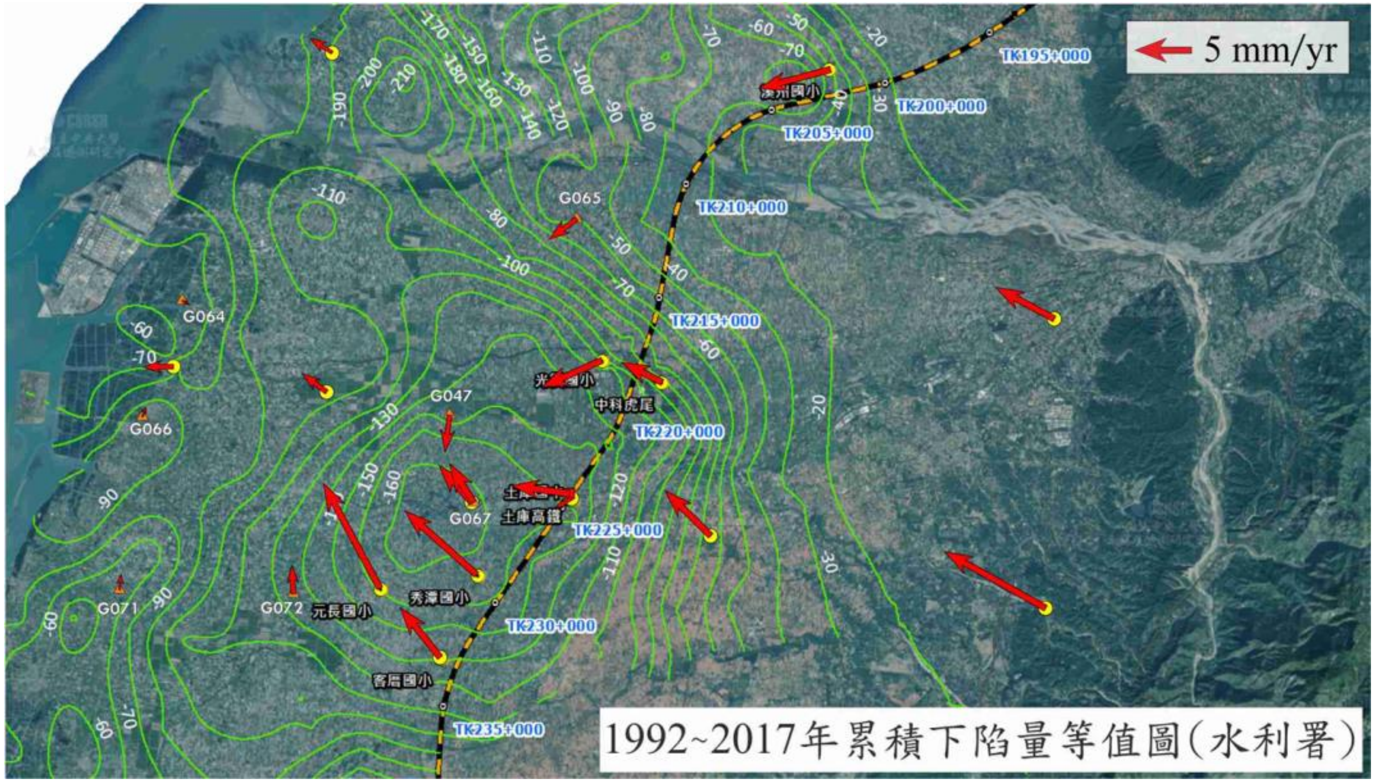

原始數據來源:水利署 & 中央地質調查所

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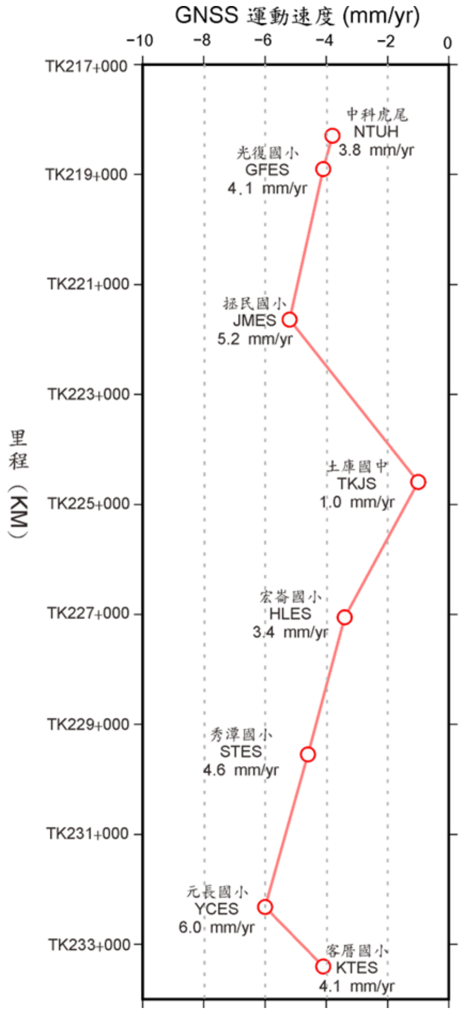

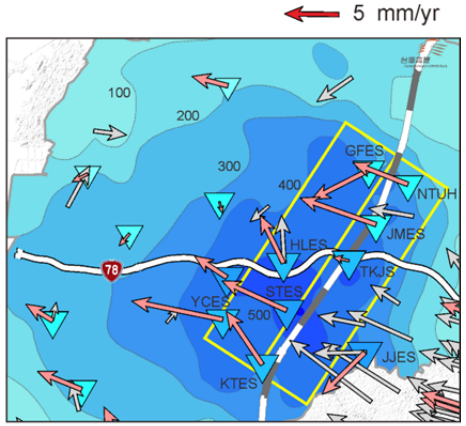

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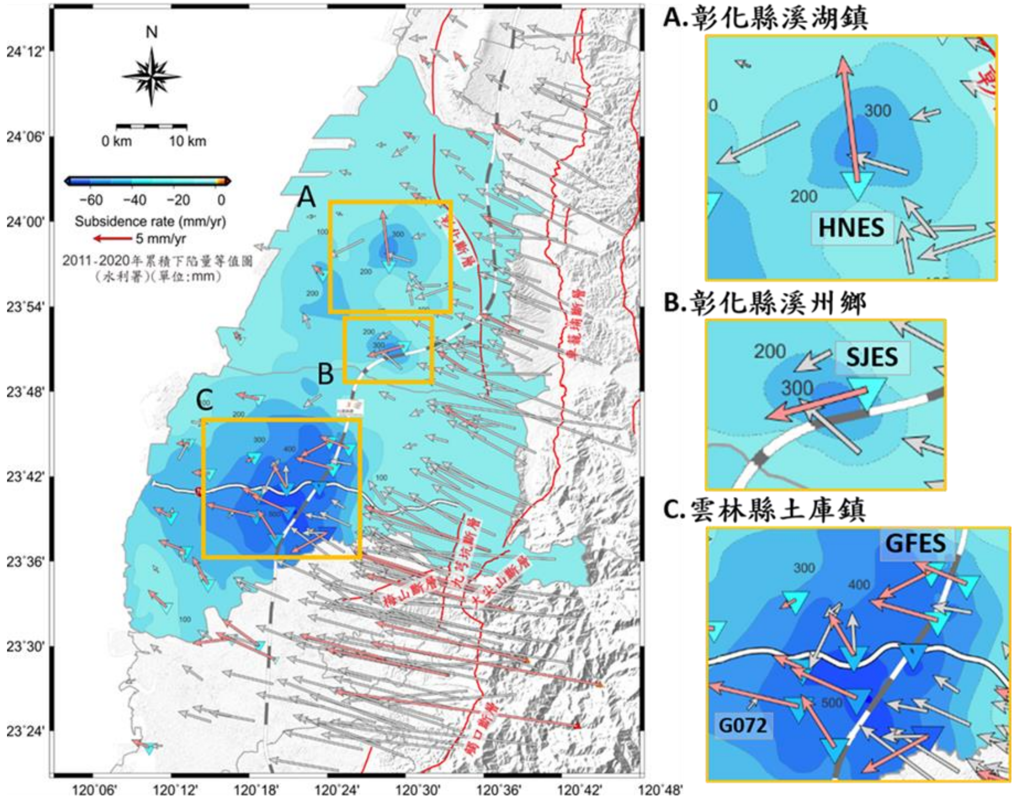

GNSS速度場圖 – 沉陷錐相關位置(2002~2020)

原始數據來源:水利署GNSS連續站及地調所GNSS連續站及移動站。
以S01R（澎湖白沙站）連續站為參考點。

1. 台灣島受版塊運動的影響，在北港高地以北，整體性之水平速度場是往西偏北，且位移速率呈漸減的趨勢。
2. 車籠埔斷層及大尖山斷層以東之水平速度量值大於30 mm/yr，並往西偏北方向運動
3. 彰化斷層及九芎坑斷層至車籠埔斷層及大尖山斷層間之水平速度量值介於10 - 30 mm/yr，也往西偏北方向運動
4. 彰化斷層及九芎坑斷層以西為西部海岸平原區，速度量值小於10 mm/yr，其運動方向並無一致性。
5. 位移趨勢指向沉陷中心；意指地層下陷可能導致鄰近沉陷錐之地面產生水平向位移，且指向沉陷中心。

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Ground Subsidence(案例一, 地層下陷)

Type IV：horizontal movement(Three subsidence centers in Tuku, Huwei, and Xizhou)

- Investigation
- Monitoring : on going
  - Ground horizontal displacement (SAA)
  - Pile structure movment(SAA)
  - GNSS on bridge level
  - Pier tilting (24 piers)
  - 3D Traverse survey on bridge level
- Ground horizontal displacement mechanism
  - 塊體模型 block model : completed
  - 錯位模型 dislocation model : completed
  - IN-SAR : ongoing
- Remedial work plan
  - Will be initiated based on monitoring data
- Remedial work construction
  - Will be initiated based on design and monitoring data

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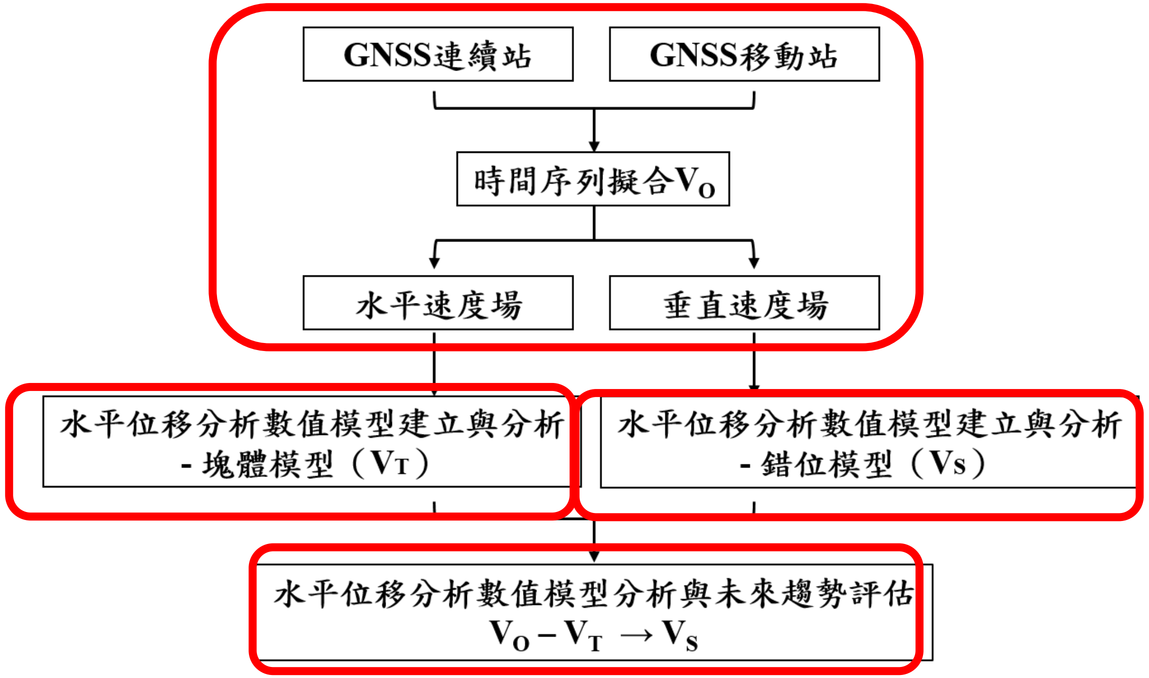


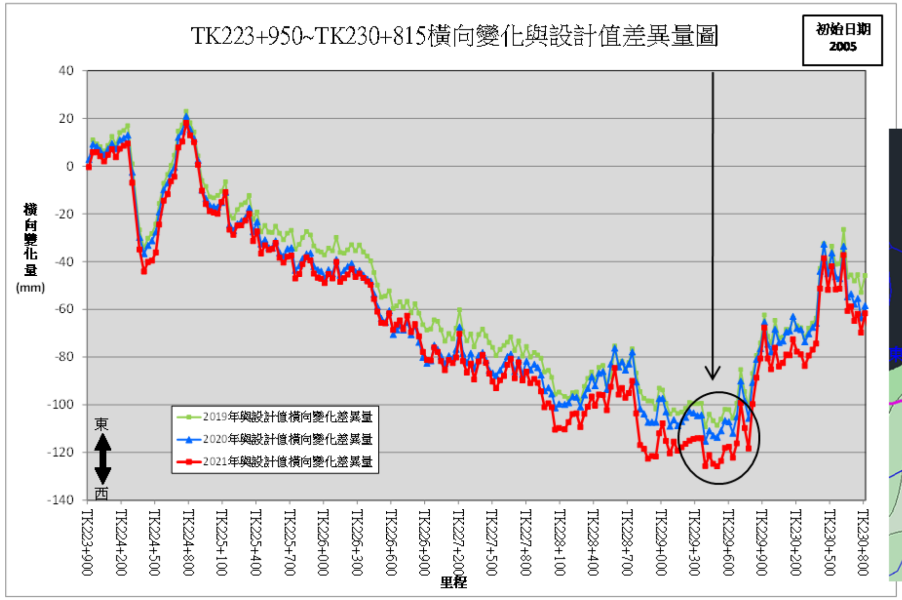
成大空間資訊系(景國恩、蔡佩京)

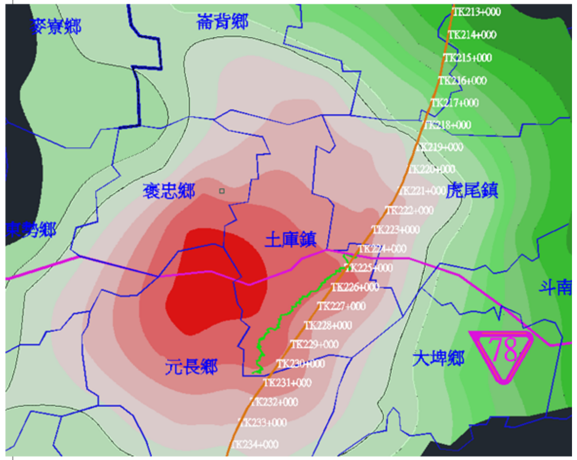
路權外環境與地質因素對鐵道構造物的影響
Impact of Environmental and Geological Issues to HSR Infrastructure Ground Subsidence(案例一, 地層下陷)

Type IV：Horizontal Movement(Three subsidence centers in Tuku, Huwei, and Xizhou)

高鐵橋面3D導線測量成果

- TK229~TK230路段鄰近雲林土庫、元長地區之沉陷中心
- 2021成果(TK224~TK231)，與設計線型相較水平差異量最大為126mm 向西，最大偏移里程在TK229+500~600附近 。





路權外環境與地質因素對鐵道構造物的影響
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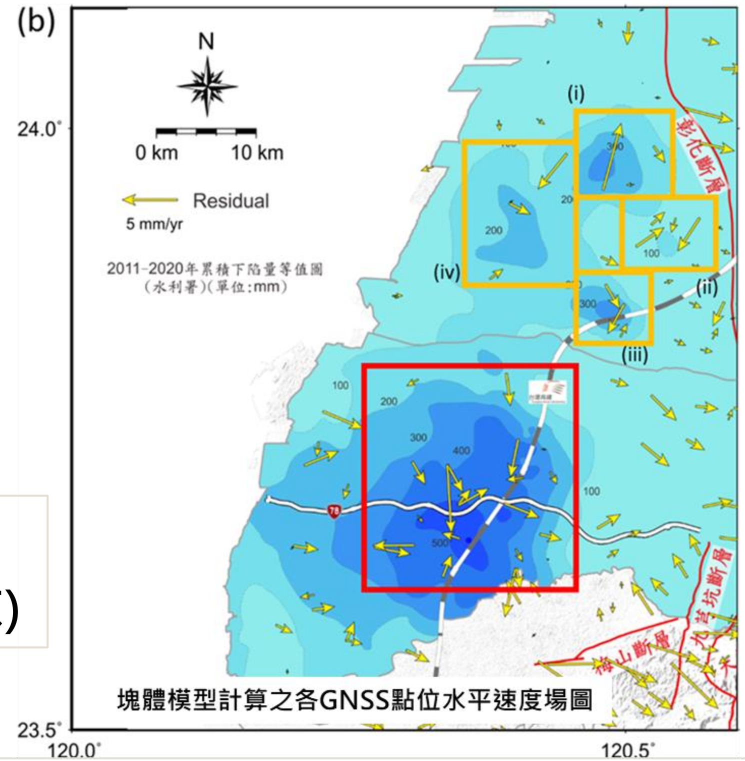

塊體模型

成大空間資訊系(景國恩、蔡佩京)

黃色箭頭則為殘差值(塊體模型正演之計算值V_T與觀測值Vo之差值)；
橘色方框為彰化地區沉陷中心位置；紅色方框為雲林地區陷中心位置

路權外環境與地質因素對鐵道構造物的影響
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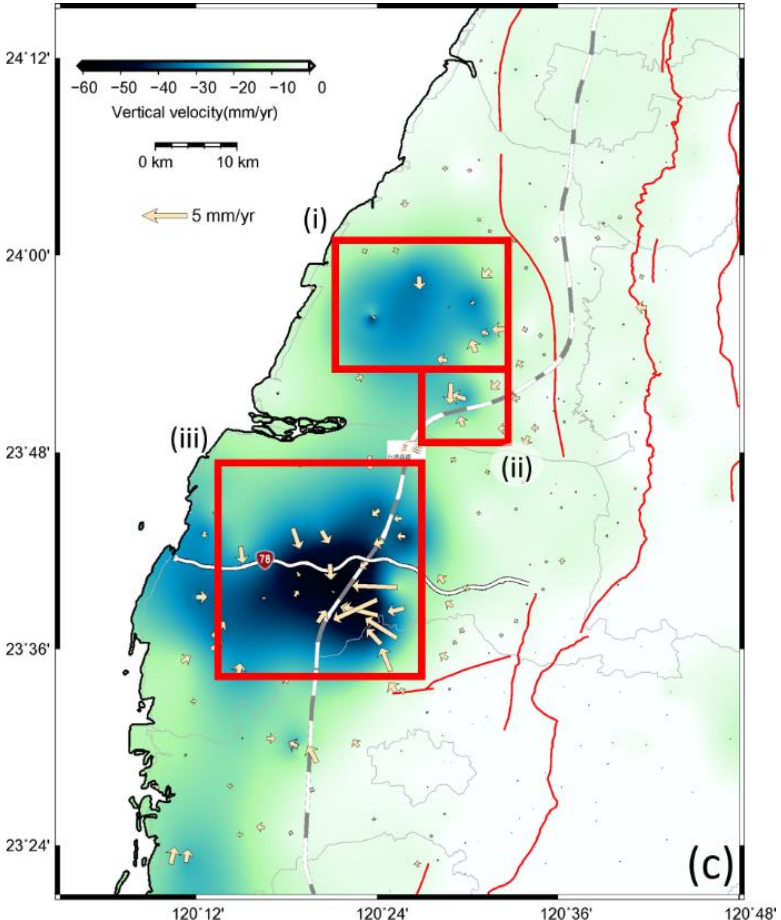

錯位模型

成大空間資訊系(景國恩、蔡佩京)

路權外環境與地質因素對鐵道構造物的影響
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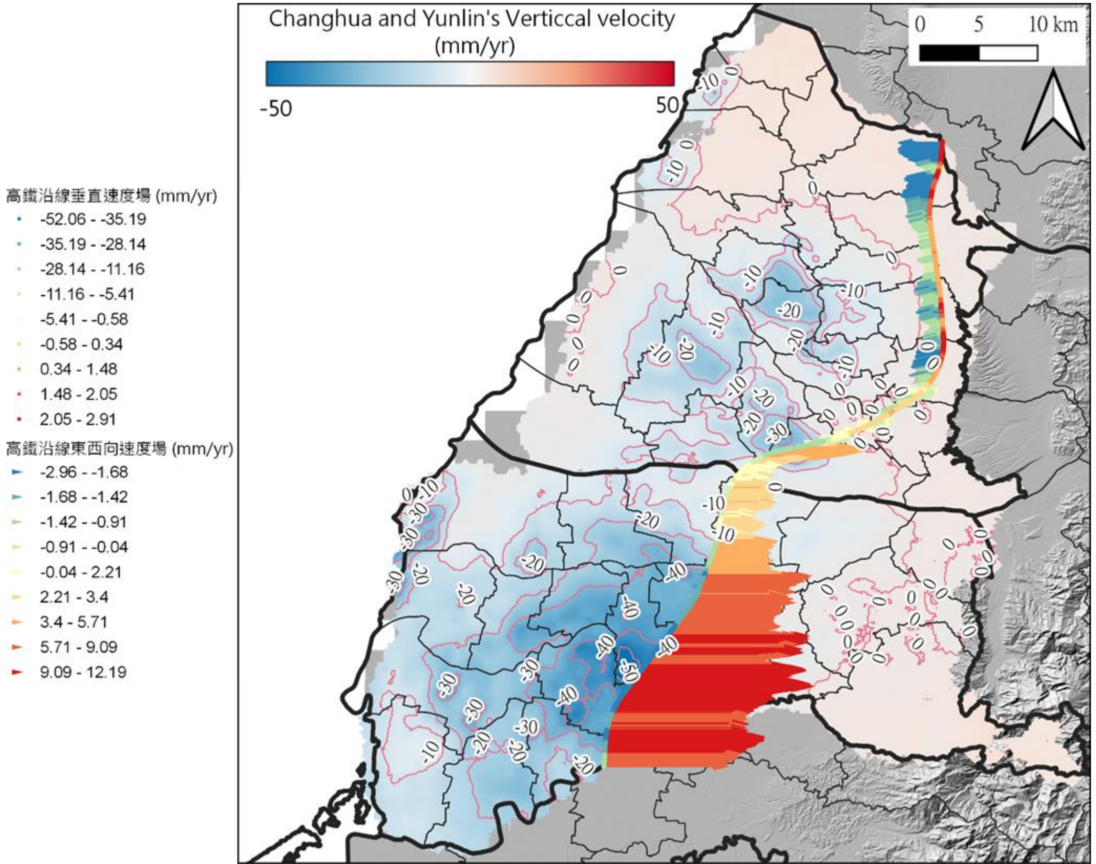
INSAR分析 : 台大胡植慶教授(9pm, 2022/8/30)



路權外環境與地質因素對鐵道構造物的影響
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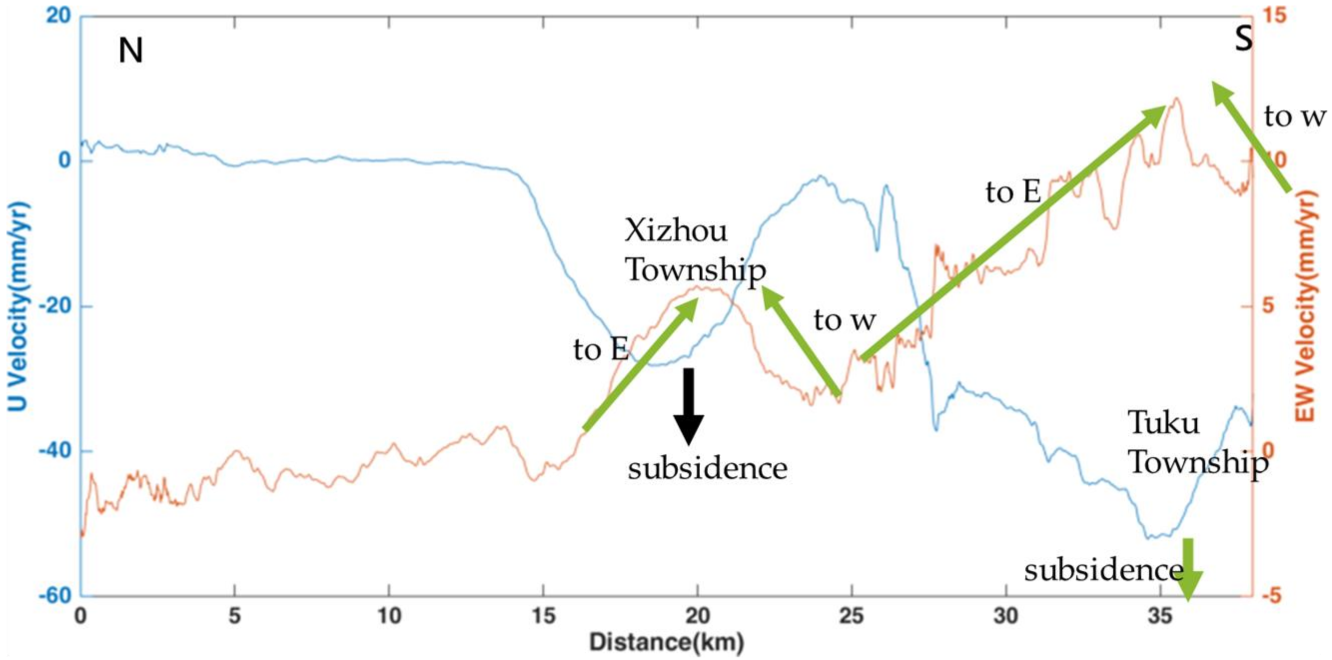

高鐵經過溪州與土庫兩個沉降中心時，其水平向位移皆有受到沉降椎的影響，在沉降中心兩側有反向的水平形變。
溪州地區的水平形變反折表現得比沉降中心更遠，應該是此處高鐵軌道偏東西向，軌道在由東向西繞過溪州沉降中心時，仍然表現得更持續向東的水平形變。

路權外環境與地質因素對鐵道構造物的影響
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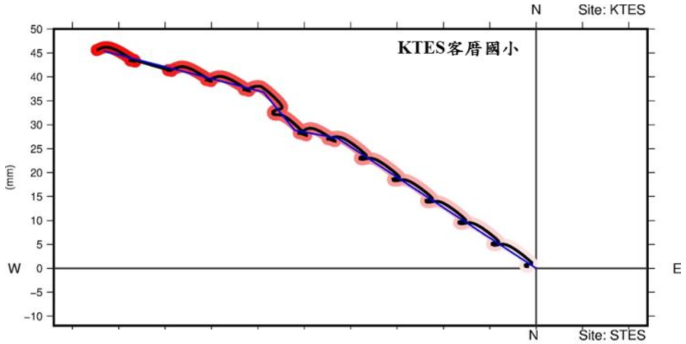

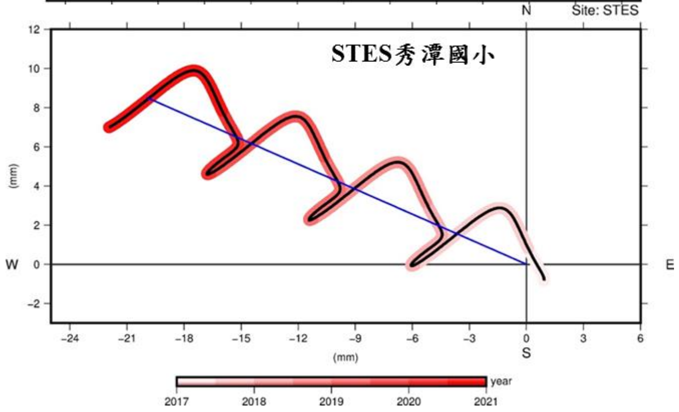

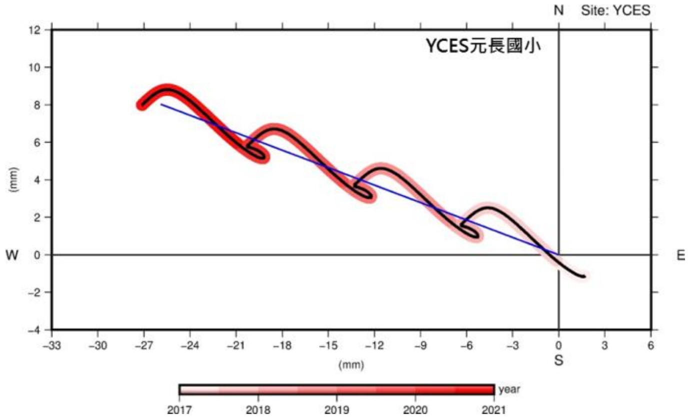

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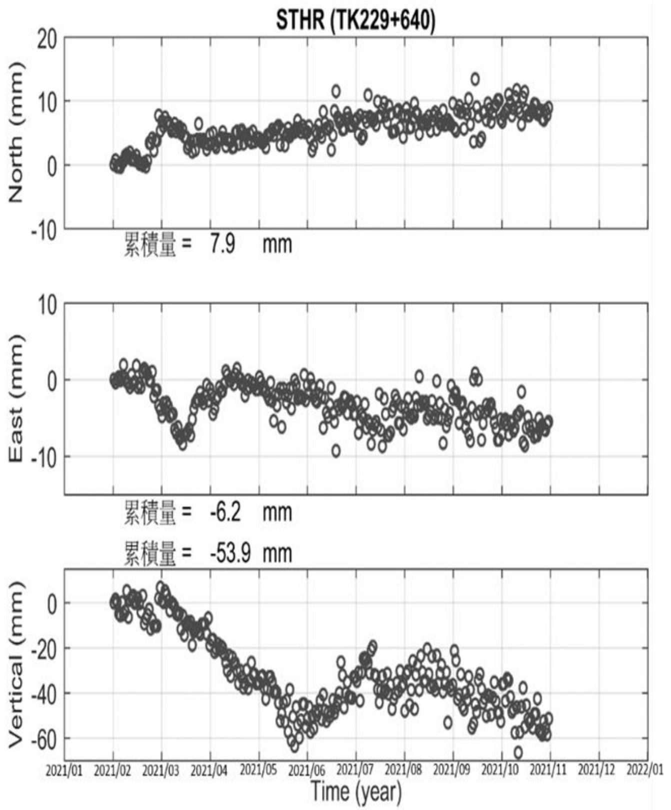

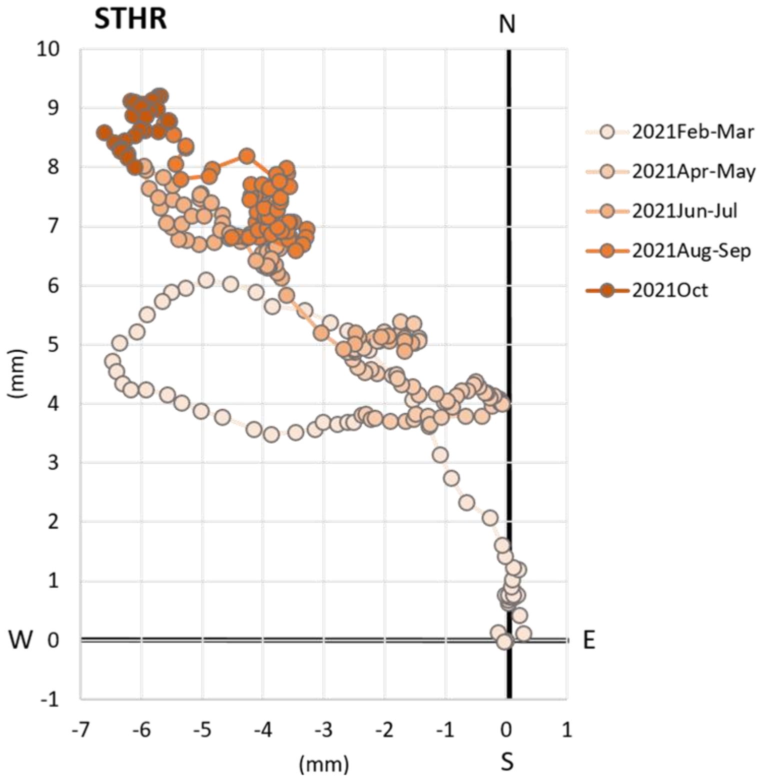

路權外環境與地質因素對鐵道構造物的影響
Impact of Environmental and Geological Issues to HSR Infrastructure Ground Subsidence(案例一, 地層下陷)

Type IV：Horizontal Movement(Three subsidence centers in Tuku, Huwei, and Xizhou)

Mechanism of horizontal displacement

1. Long Term Tectonic movement
2. During the development of subsidence center
3. During seasonal ground water fluctuation

路權外環境與地質因素對鐵道構造物的影響
Impact of Environmental and Geological Issues to HSR Infrastructure Ground Subsidence(案例一, 地層下陷)

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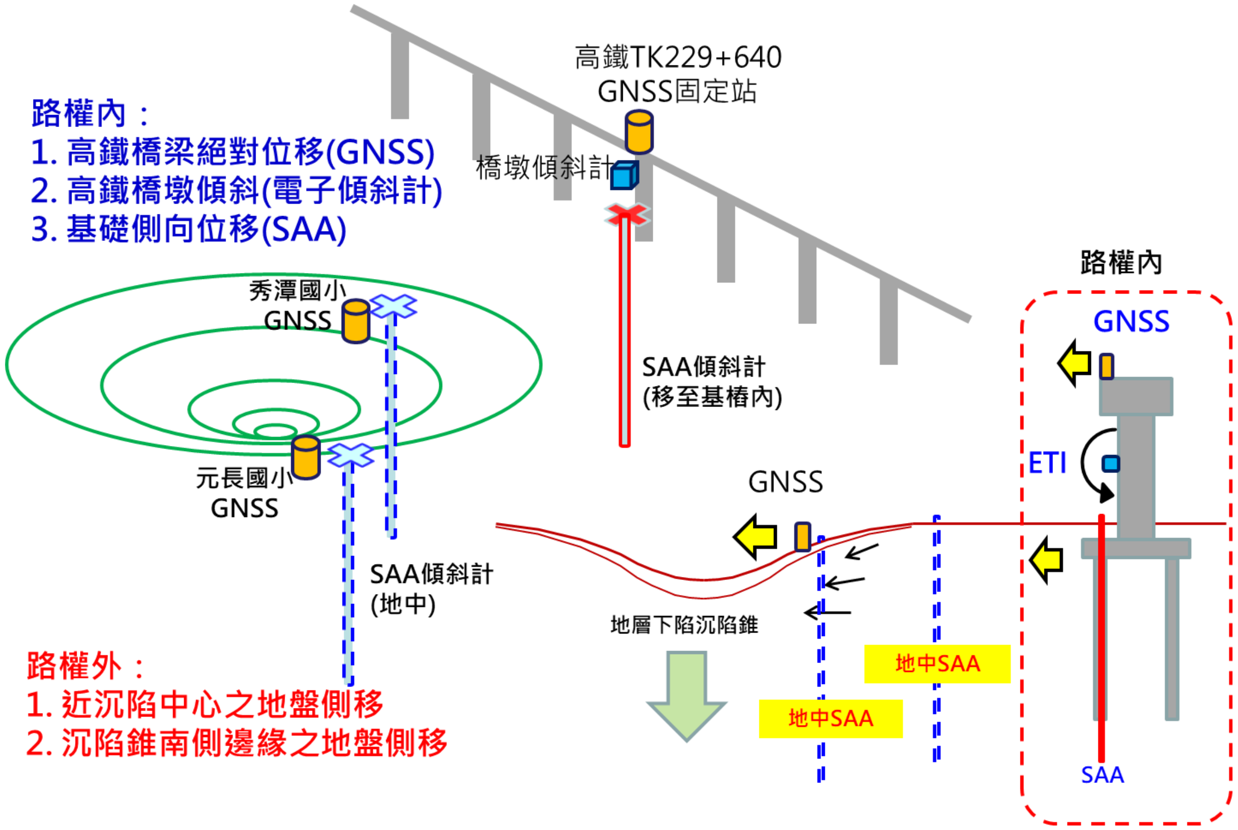
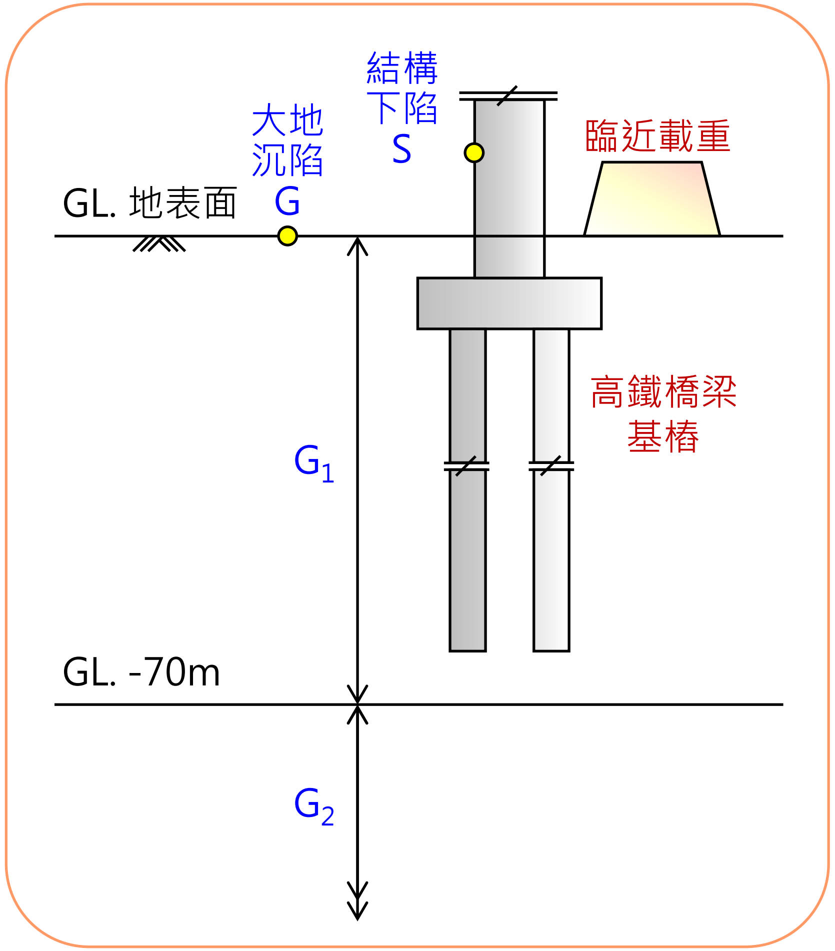


路權外環境與地質因素對鐵道構造物的影響
Impact of Environmental and Geological Issues to HSR Infrastructure
Ground Subsidence(案例一, 地層下陷)



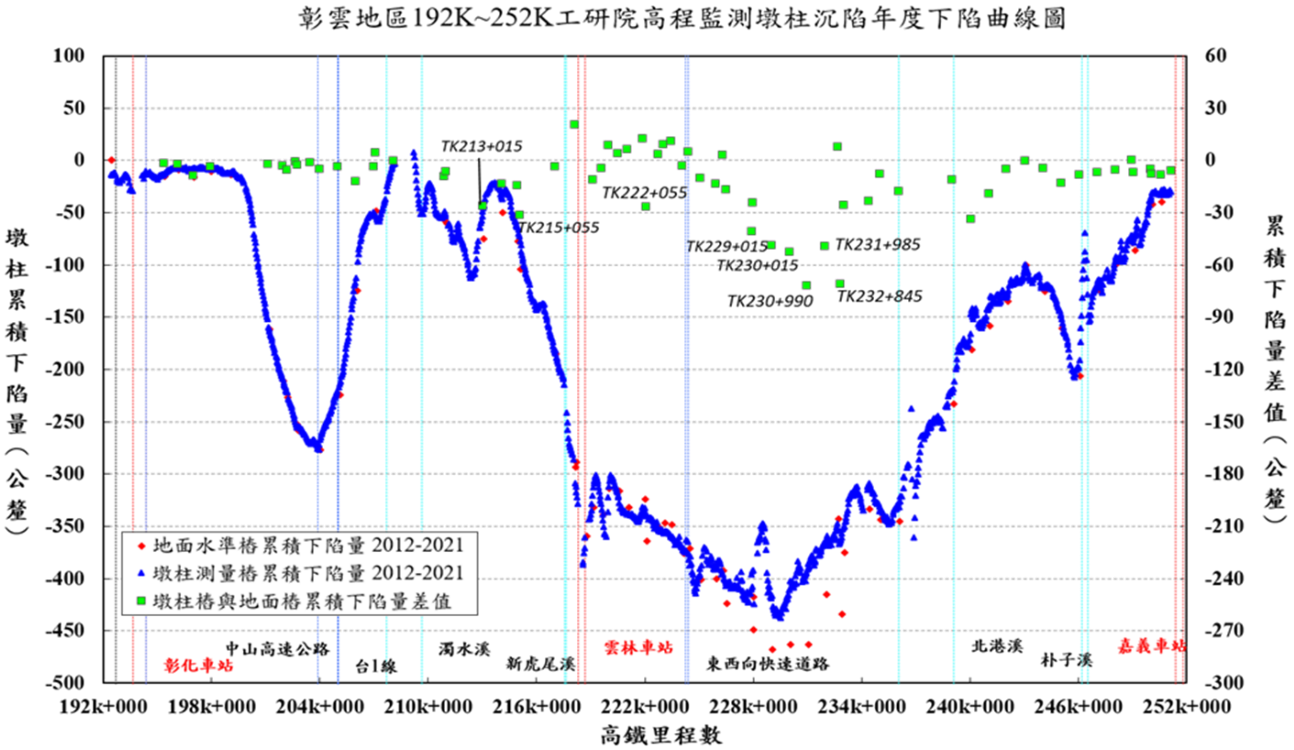
$G = G_1 + G_2$

地表量測之沉陷 = 各土層壓縮之總和

情境	土層壓縮分佈	原因
G > S TPYE 二 TYPE三 TYPE 四	GL.0~-70m 土層壓縮明顯	① 淺層壓縮 ② 土庫地區(TK228~230) 後果：易受地表超載、乾旱的影響，基樁可能發生額外下陷(基樁負摩擦力)
G = S TYPE 一	GL.0~-70m 土層沒有壓縮	① 結構與大地同步沉陷 後果：對高鐵沒有影響
G < S	結構下陷 > 大地沉陷	① 易發生在TK228~230 ② 基礎承載力不足 ③ 後果：需補強

路權外環境與地質因素對鐵道構造物的影響
Impact of Environmental and Geological Issues to HSR Infrastructure Ground Subsidence(案例一, 地層下陷)

Ground Settlement > Pier Settlement in Tuku Area



路權外環境與地質因素對鐵道構造物的影響
Impact of Environmental and Geological Issues to HSR Infrastructure
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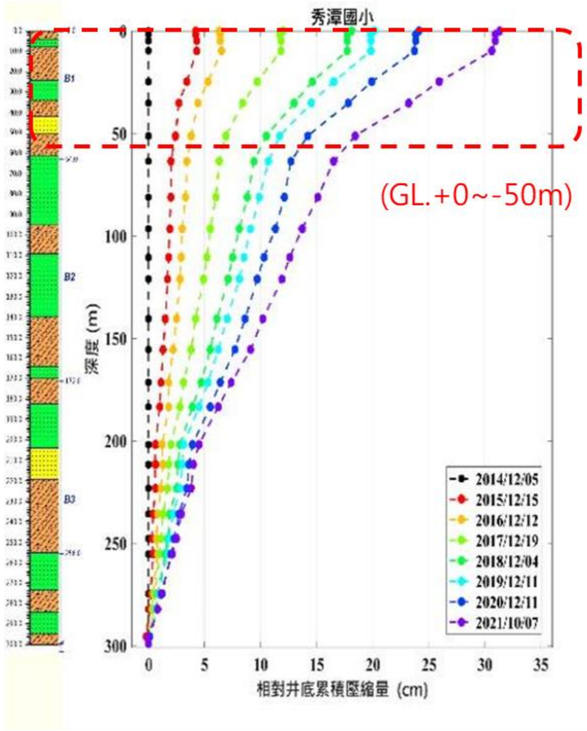
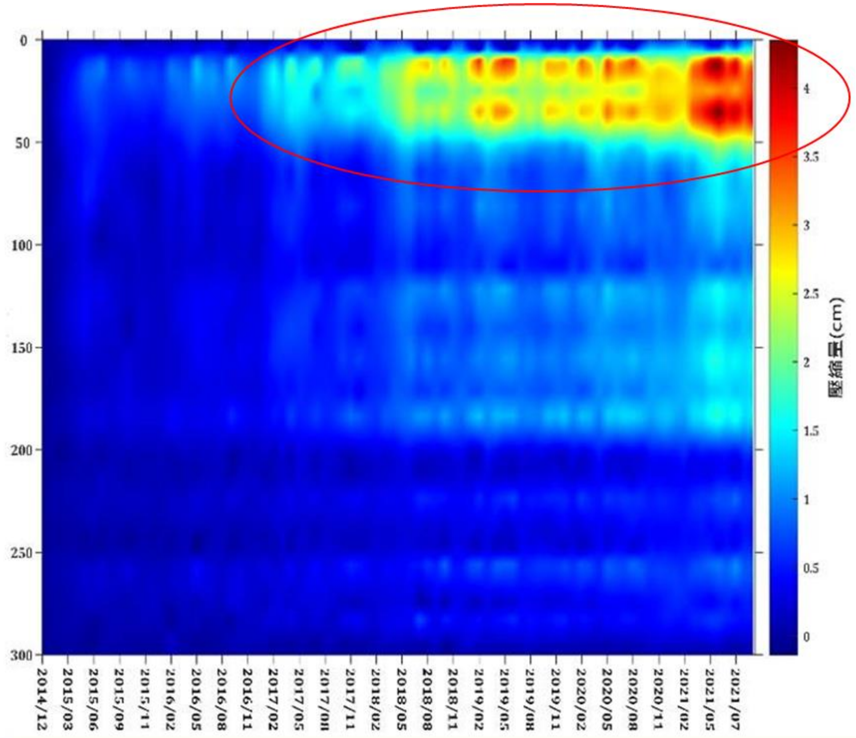




資料來源: 水利署2021/10

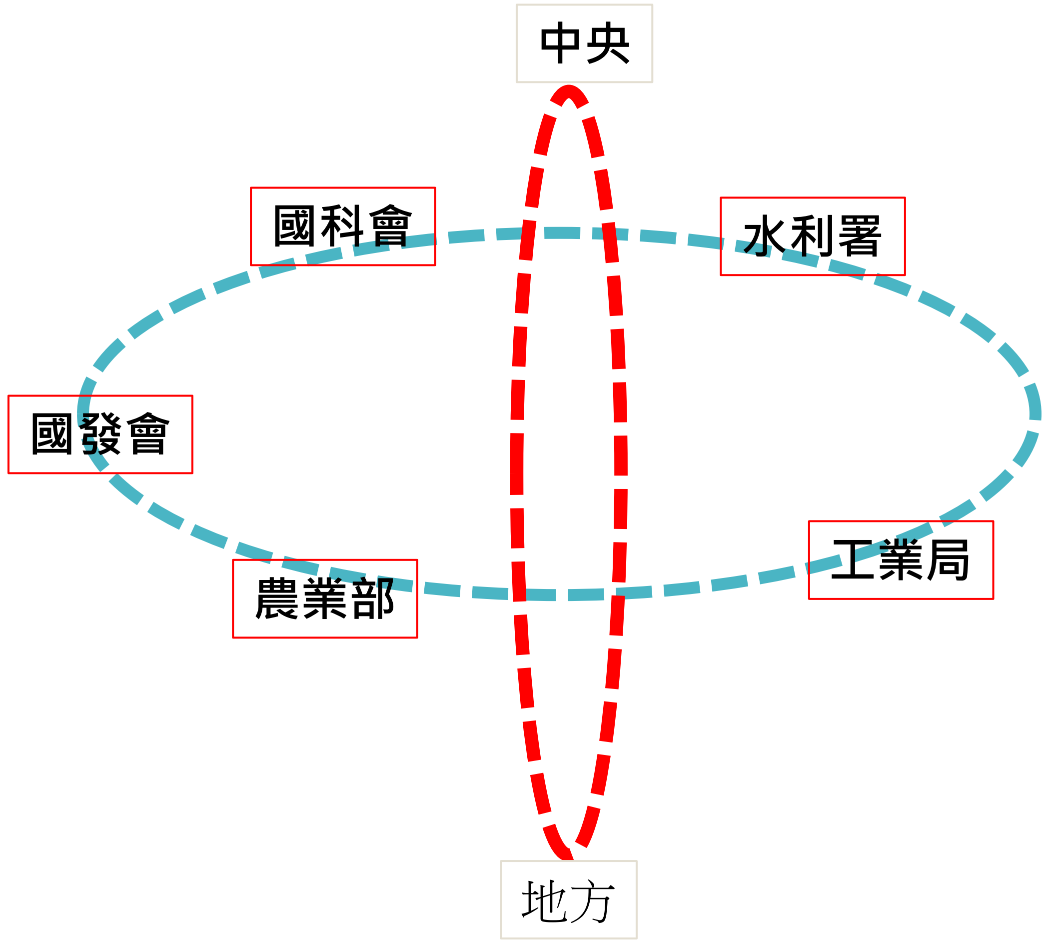
路權外環境與地質因素對鐵道構造物的影響
Impact of Environmental and Geological Issues to HSR Infrastructure
Ground Subsidence(案例一, 地層下陷)

Conclusions & Suggestions

1. Political football kick around for many years. It ends up with nothing.

2. Ground subsidence issue should be defined clearly,
   1) Regulation enforcement ?
   2) R&D?
   3) Monitoring?
   4) Water Supply?

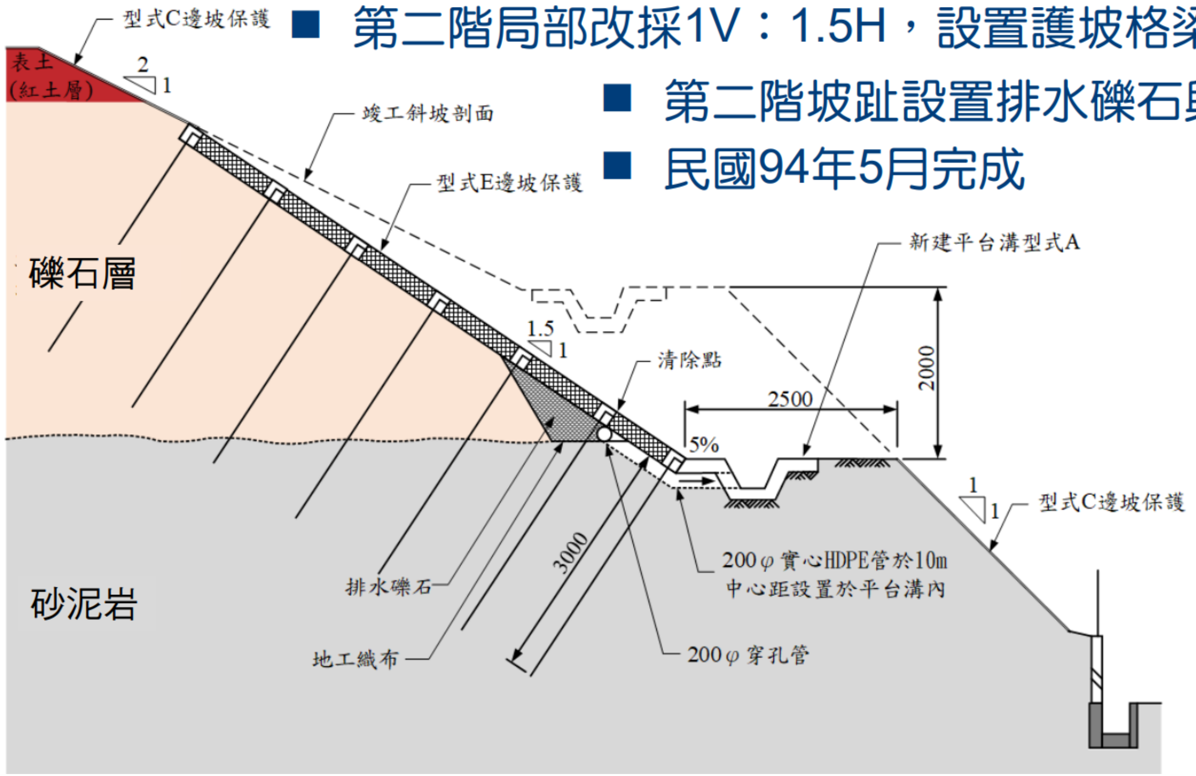
1. Be practical

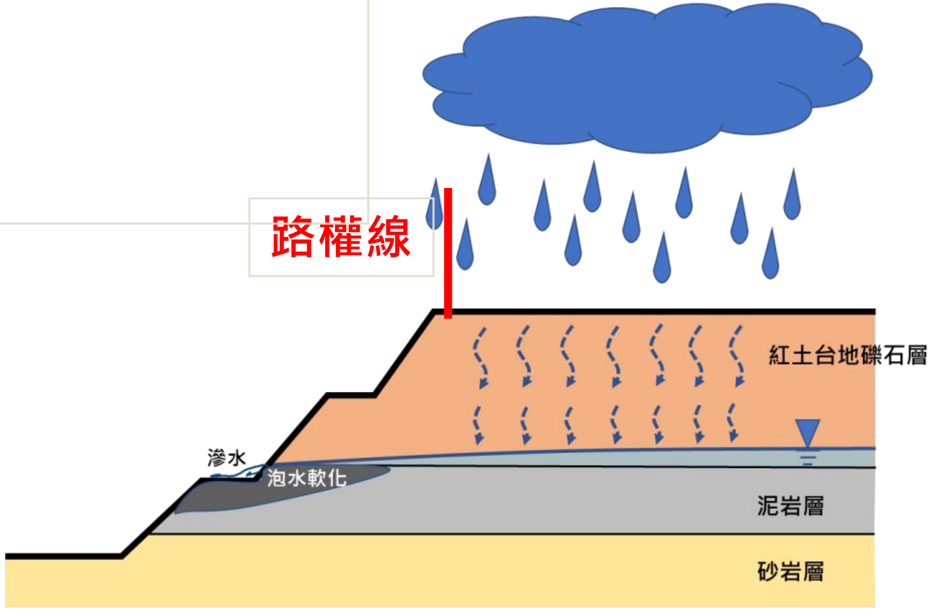


案例探討 – 邊坡問題

❖ 20040706 坍滑修復

- 清除回填材料與風化岩層
- 第一階頂部平台面降挖2公尺
- 第二階局部改採1V：1.5H，設置護坡格梁及錨釘
- 第二階坡趾設置排水礫石與地工織布
- 民國94年5月完成





案例探討 – 邊坡問題

TK126邊坡坍滑發生機制漸進式後退破壞

I 階段
8/7 8:00~9:00
(下方坡體坍滑)

II 階段
8/7 9:00~9:30
(上方坡體失去支撐、發生坍滑)

案例探討 – 邊坡問題

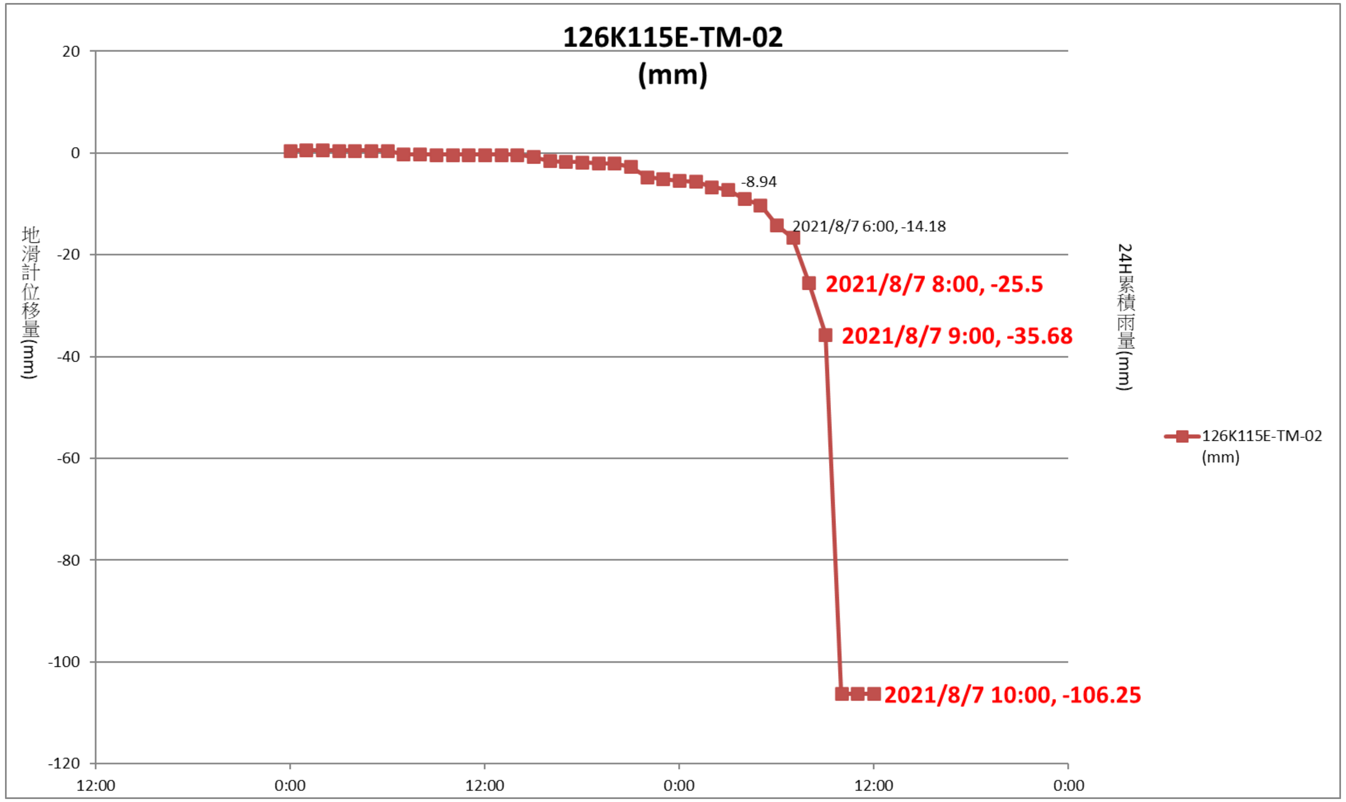
TK126邊坡坍滑發生機制漸進式後退破壞

1. 8/7 8:00~9:00 下方坡體坍滑
   - ✓ 第一階邊坡發生破壞觸動DWS
   - ✓ 並誘發第二階邊坡發生全面滑動
2. 8/7 9:00~9:30 上方坡體失去支撐、發生坍滑
   1. 第二階坡趾鬆動
   2. =>第二階卵礫石層沿岩層界面滑動
   3. =>RC格梁向下滑動
   4. =>RC格梁損壞
   5. =>坡面崩壞
   6. =>紅土礫石層產生滑動

案例探討 – 邊坡問題

TK126邊坡坍滑發生機制漸進式後退破壞

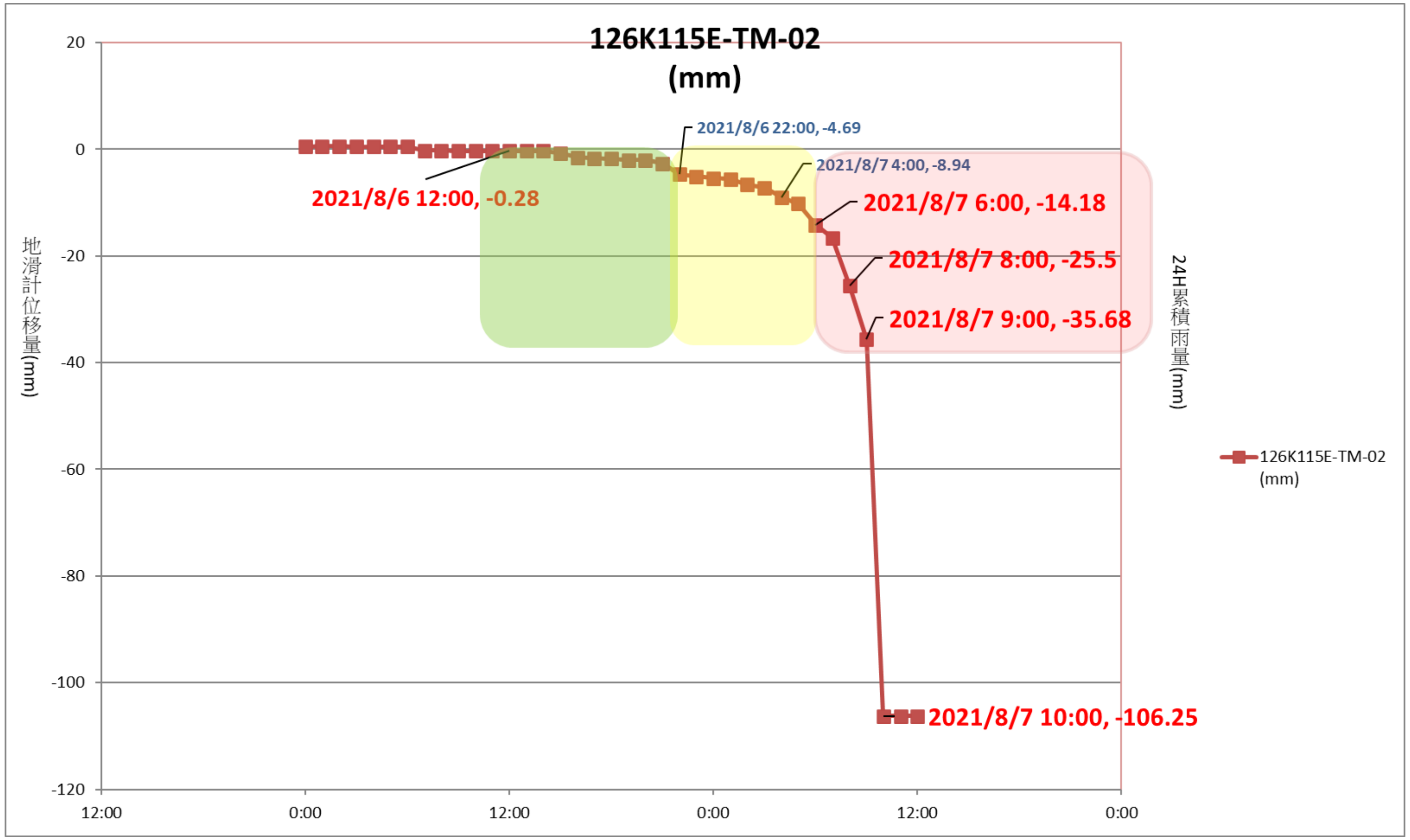
1. **8/7 8:00~9:00 下方坡體坍滑**
   - ✓ 第一階邊坡發生破壞觸動DWS
   - ✓ 並誘發第二階邊坡發生全面滑動
2. **8/7 9:00~9:30 上方坡體失去支撐、發生坍滑**
   1. 第二階坡趾鬆動
   2. =>第二階卵礫石層沿岩層界面滑動
   3. =>RC格梁向下滑動
   4. =>RC格梁損壞
   5. =>坡面崩壞
   6. =>紅土礫石層產生滑動



案例探討 – 邊坡問題
TK126邊坡坍滑發生機制漸進式後退破壞

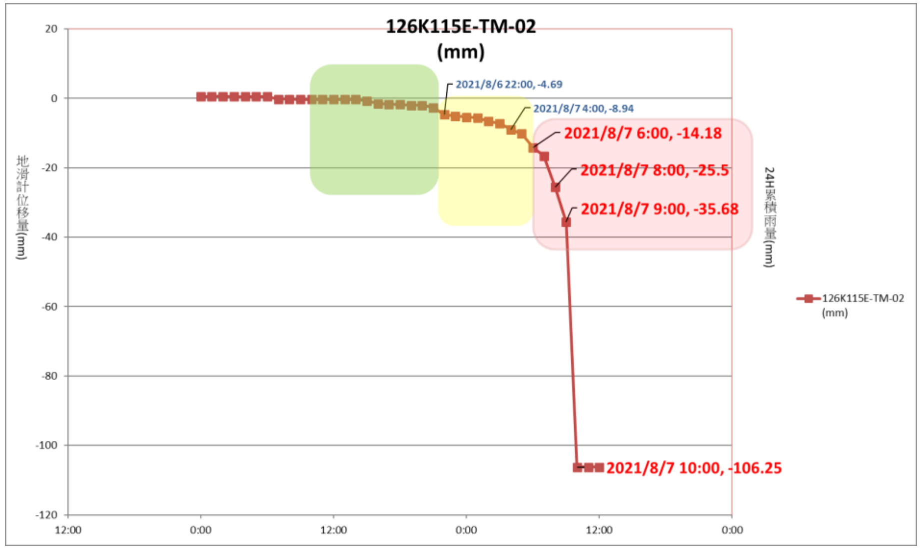
邊坡位移從啟動到破壞< 24小時

1) 08/06 12:00 開始
2) 08/07 04:00 開始加速
3) 08/07 08:00 高速位移
4) 08/07 10:00 全面破壞



案例探討 – 邊坡問題
Lessons Learned (TK126)

1) Time required to reach fully failure <24 hrs. Displacement level for management shall consider
   1) 配合營運安全的要求 mobilization to ensure operational safety
   2) 有效的監測 capability of monitoring device
2) The concept of safety factor can not reflect slope displacement and time.



表四　滑動速率與邊坡穩定性判斷建議表(日本地滑對策技術協會，1978)

變動種別	日變位量(mm)	月變位量(mm)	一定方向的累積傾向	活動性判斷	摘要
緊急變動	20以上	500以上	非常的顯著	急速崩壞	崩壞型 泥流型
確定變動	1以上	10以上	顯著	活潑運動中	崩積土滑動 深層滑動
準確定變動	0.1以上	2以上	略顯著	緩慢運動中	黏土滑動 回填土滑動
潛在變動	0.02以上	0.5以上	稍稍有	有待繼續觀測	黏土滑動 崖積滑動

Ref : 地工技術136, 2013

案例探討 – 邊坡問題
Lessons Learned (TK126)

表八　日本與台灣在不同地滑案例管理值主要差異表

比較項目／管理值	日本案例		台灣案例	
	地表伸縮計	傾斜觀測管	伸縮計(含地表型及孔內型)	傾斜觀測管
注意值(注意體制)	1~4mm/時	無此項目	0.5~1mm/月	0.5~2mm/月
警戒值(警戒體制)	1~10mm/時	無此項目	2~10mm/月；20mm/7日；0.5mm/日	2~20mm/月
行動值(避難體制)	4~40mm/時	10mm/時(孔內傾斜計)	1~32mm/日	1~5mm/日；10mm/月

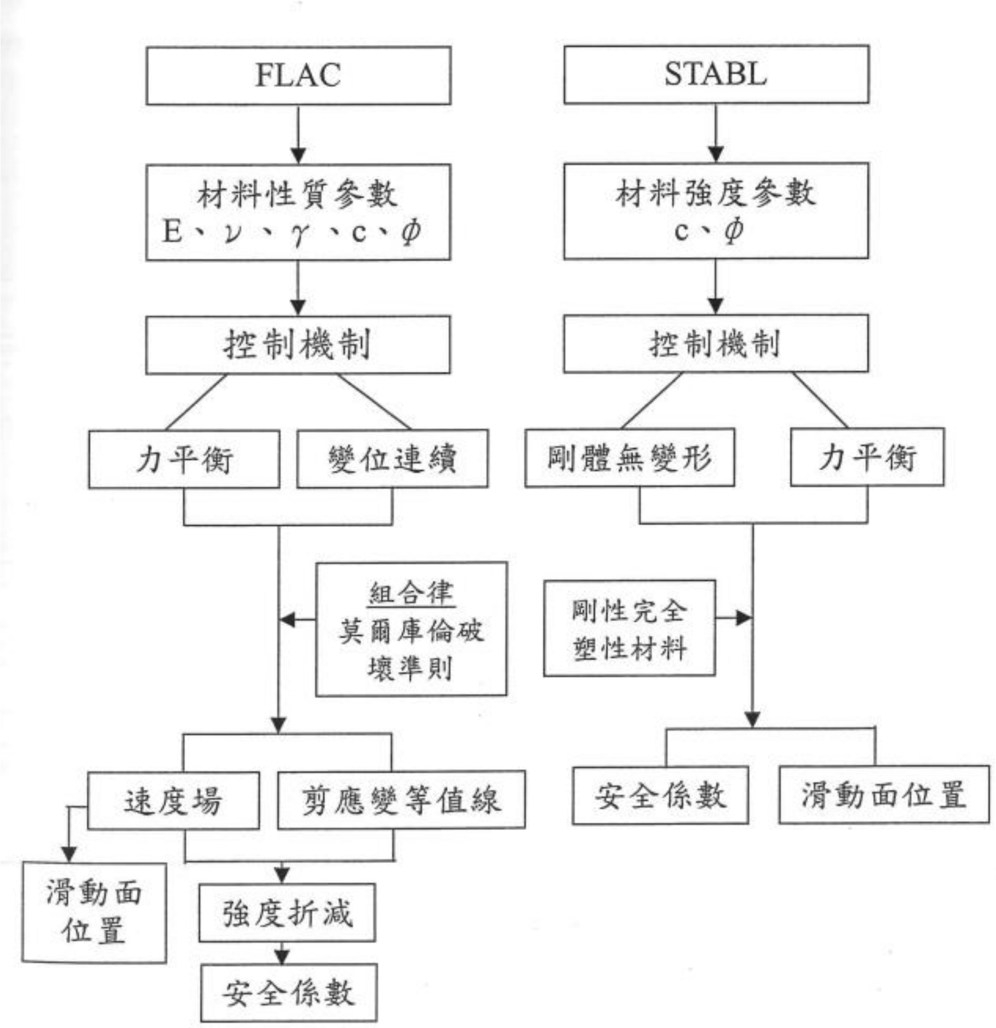
Ref : 地工技術136, 2013

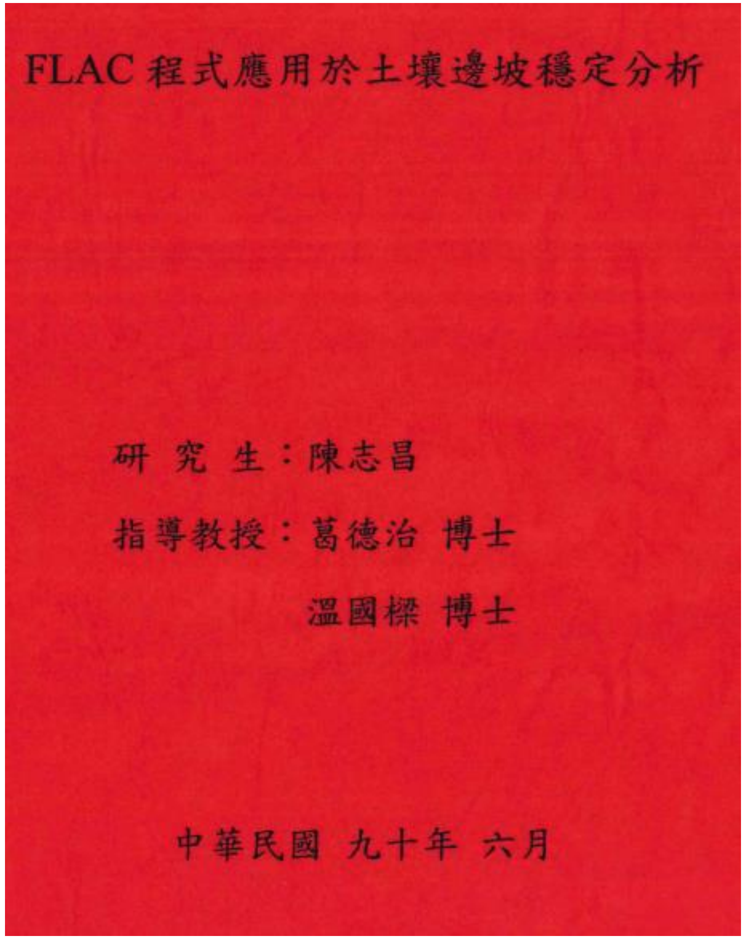
案例探討 – 邊坡問題 Lessons Learned (TK126)

問題

1. 邊坡安全係數無法反應邊坡位移
2. 邊坡破壞所需時間甚短，從注意值、警戒值到行動值幾乎瞬時發生
3. 目前文獻建議的管理值決定的依據不符合實際，不具操作性
4. 監測儀器無法量測
5. 邊坡安全管理者沒有時間辦理警戒或採取行動

案例探討 – 邊坡問題
Lessons Learned (TK126)




FLAC 程式應用於土壤邊坡穩定分析

研 究 生：陳志昌

指導教授：葛德治 博士

溫國樑 博士

中華民國 九十年 六月

Thanks for your attention