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DISPLACEMENT BEHAVIOR OF A LINE-SHAPED ELEVATED STRUCTURE DUE TO CRUSTAL DEFORMATION IN SW TAIWAN

H.W. Yang[1], Chuan Ding[2], S.K. Ho[3], K.E. Ching[4]

[1] Engineering Director, Taiwan High Speed Rail Corporation, hw_yang@thsrc.com.tw
[2] Engineering Geologist, Sino-Geotechnology, Inc.
[3] Chief Engineer, Sino-Geotechnology, Inc.
[4] Professor, National Cheng-Kung University

Abstract

Taiwan is situated at the junction of the Manila and Ryukyu subduction systems, and is a typical example of the ongoing arc-continent collision due to the convergence between the Eurasian and Philippine Sea plates. The plate convergence rate across the island is about 80 mm/yr in the direction of N310°E. Long-term GPS observations demonstrate that the material in SW Taiwan is forced to extrude toward WSW, sub-parallel to the edge of the stable continental margin, via strain partitioning along several major fault structures, as a result of the interaction between the Peikang Basement High and westward propagation of the Philippine Sea plate. Data from GPS and leveling surveys further indicate that a distinct discontinuity in crustal movement exists with respect to both direction and magnitude across the CHNF creeping fault.

The alignments of line-shaped transportation infrastructure in SW Taiwan have been strongly affected by crustal deformation in both lateral and vertical directions. This paper first introduces the background of regional crustal deformation due to tectonic movement, followed by contemporary observed displacement behaviors of an elevated structure from the bedrock, ground level, pile structure, pier structure, and elevated superstructure at the deck level. Furthermore, this paper proves that the short term uplift rates measured by leveling surveys on the elevated structure conform to the pattern of long term uplift rate of crustal displacement in the area across the creeping fault, based on studies of radiocarbon dating (^{14}C) and nannofossil analysis.

Keywords: crustal displacement; elevated viaduct structure; pile foundation

1. Introduction

The alignment of line-shaped transportation infrastructure in SW Taiwan has been strongly affected by crustal deformation resulting from island-wide tectonic movement and creeping faults. Field records indicate longitudinal and uplift displacements of freeway viaducts and tunnel structures have been occurring since 2000. The associated movements are about 8 cm/yr in uplift and 6 cm/yr lateral displacement in the SW direction. In addition, the alignment of the railway in this region has been progressively shifted toward the SW by about 40 cm since the initial readings taken in 2000. Data from monthly track geometry measurements indicate that the distortion of the geometry has been taking place continuously. In order to comprehensively assess how long the structural capacity of the viaduct structure can resist the crustal movement from the creeping fault, given its 100 year design life, a three stage investigation program was initiated in 2015. The scope of Stage I included a geological investigation to locate the creeping fault across the railway alignment, and monitoring of the displacement behavior of the elevated structure and ground. The work in Stage II will focus on a safety assessment of the pile foundations and superstructure under crustal movement, together with various load combinations specified in the design specifications. Stage III will conduct preventive maintenance work, if necessary. This paper presents the findings from the work conducted in Stage I.

2. Crustal deformation in SW Taiwan

The crustal deformation in SW Taiwan is complicated, because of the thick mudstone formations and the movement of active faults, including the Chishan Fault (CHNF), the Lungchuan Fault (LCNF), the Chekualin Fault (CKNF), and the Hsiaokangshan Fault (HKSF) (Figure 1).

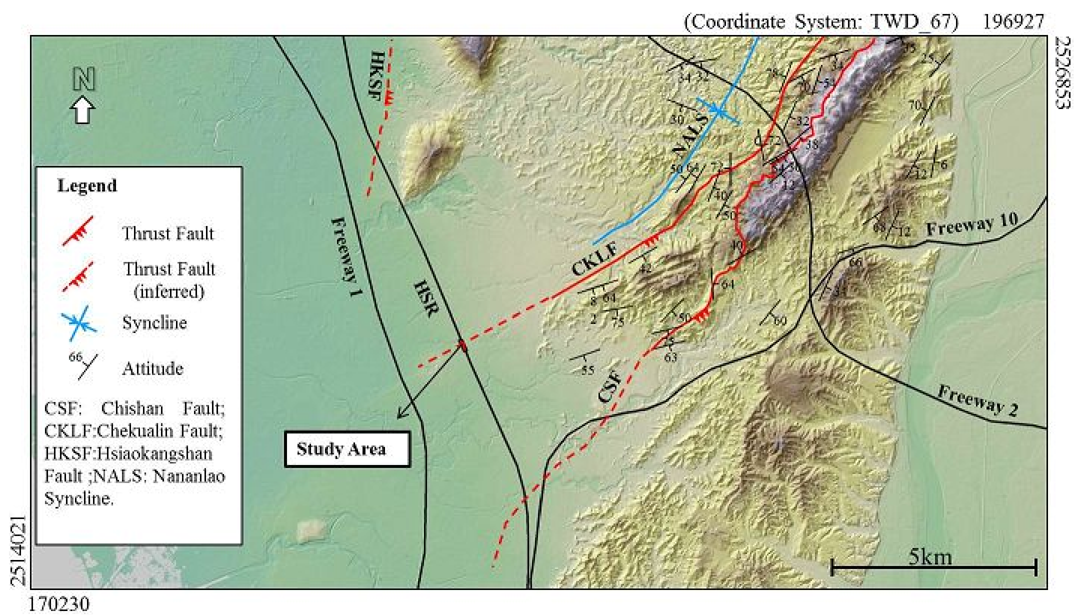

Fig. 1. Major faults and major transportation alignment in SW Taiwan

2.1 Tectonic setting

The island of Taiwan is located at the plate boundary between the Eurasian (EUP) and Philippine Sea (PHP) plates, and is bounded by two subduction zones. In the north, the PHP subducts beneath the Ryukyu Arc, while to the south, the South China Sea block of the EUP subducts beneath the PHP (Figure 2). The Taiwan orogeny results from the collision of the Luzon volcanic arc in the PHP and the Chinese continental margin in the EUP beginning about 3–6 Ma ago [1]. The convergence across the Taiwan arc-continent collision zone inferred from the GPS velocity field is about 82 mm/yr in the northwest direction [2].

Taiwan can be divided into six northeast-trending physiographic regions that are separated by major faults (Figure 2). They are, from west to east, the Western Coastal Plain, the Western Foothills, the Hsueshan Range, the Central Range, the Longitudinal Valley, and the Coastal Range. SW Taiwan is located at a transition zone between subduction and collision, and is surrounded by the Central Range in the east, the Western Foothills in the west, and an alluvial plain at the southern end of the Western Foothills. It is worth noting that an at least 5-km-thick sequence of mudstone belonging to the Gutingkeng Formation (Plio-Pleistocene) is the dominant lithology in this region.

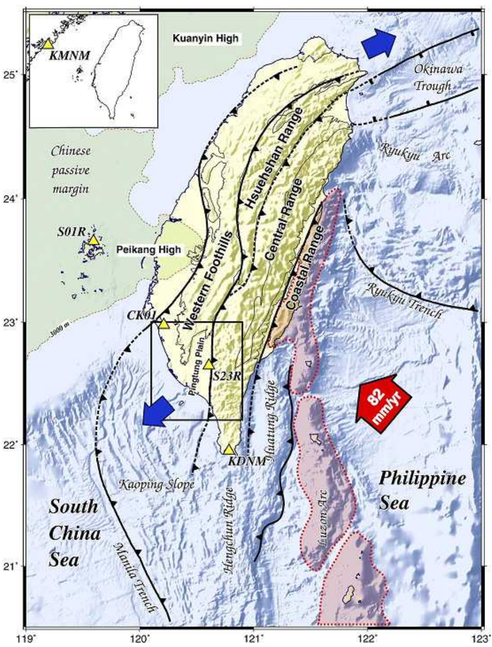

Fig. 2. Geotectonic framework and major structural units of Taiwan

2.2 Characteristics of crustal deformation in SW Taiwan

According to the concept of tectonic escape describing the kinematic motion of geological units towards a free boundary, it has been proposed that the material in SW Taiwan is being forced to extrude towards the WSW, sub-parallel to the edge of the Peikang basement high, which is oriented at N55^{0}E, by the westward propagation of the Philippine Sea plate [3]. Considering the impact to the existing line-shaped transportation infrastructure in SW Taiwan, in this paper we will explore the effects of the movements along two faults, namely the LCNF and the CHNF.

The CHNF is the major boundary fault in SW Taiwan. In addition to the tectonic escape model [4, 5] propose a revised tectonic kinematic model, as shown in Figure 3, to describe the modern crustal deformation in SW Taiwan. These authors point out that the CHNF separates SW Taiwan into two structural domains. On the west side of the CHNF is the internally deforming Western Foothills consisting of mudstone, whereas on the east side of the CHNF is the relatively rigid Pingtung Plain consisting of sandstone. The horizontal velocities on the west side of the CHNF decrease rapidly westward from 42.0 mm/yr to 13.0 mm/yr along azimuths ranging from 246° to 265° across SW Taiwan. In contrast, the velocities from most (~95%) of the stations east of the CHNF are quite consistent (51.9±6.6 mm/yr), along azimuths which change gradually from 277° to 247°, with a clear pattern of counterclockwise rotation. The vertical velocities indicate that a subsidence rate of 5 to 20 mm/yr is concentrated in the coastal plain, with an uplift rate of 10 to 20 mm/yr in the Western Foothills and the Central Range.

The LCNF is situated in mudstone and lies on the west side of the CHNF, approximately 500 m away at the narrowest point. A section of freeway that crosses over the two-fault system with a viaduct sited on shallow foundations and a cut-and-cover tunnel have experienced significant deformation since completion in 1999. Survey data indicate that the joints in the viaduct structure are shortening at a rate of 5 cm/yr, whilst uplift of the tunnel structure at the section crossing over the CHNF is up to 8 cm/yr. Therefore, it is clearly worthwhile improving our understanding of the surface deformation in the section crossing the two faults from an engineering point of view.

To characterize the surface deformation pattern, data from a GNSS-based geodetic network were collected and analyzed, which indicate a velocity discontinuity crossing the CHNF and LCNF [6]. Figure 4 shows the 3D velocity profile, including fault-parallel (a) and fault-perpendicular (b) components of horizontal velocities, and vertical (c) velocities. The area in this study, spanning across the CHNF and LCNF, is divided into three blocks for convenience. Blocks I, II, and III are at the footwall of LCNF, the hanging wall of LCNF (or the footwall of CHNF), and the hanging wall of CHNF, respectively. Blocks I and II are to the west of the CHNF and belong to a deforming domain. Block III is to east side of the CHNF situated on rigid sandstone. Approximately 10 mm/yr left-lateral movement is observed across the LCNF, whereas approximately 10 mm/yr right-lateral movement is found across the CHNF. The active movement in fault-perpendicular direction in Block II is more notable than that in the other two blocks. About 30 mm/yr and 50 mm/yr velocity changes have been recorded compared to the movement in Blocks I and III, respectively. Uplift rates of about 80 mm/yr is recorded in Block II across the CHNF. It has been interpreted that the CHNF acts as a high-angle, creeping, normal fault with right-lateral strike-slip motion, whereas the LCNF acts as a locked, thrust fault with left-lateral strike-slip motion, and a very shallow locking depth of 0.1 km [6].

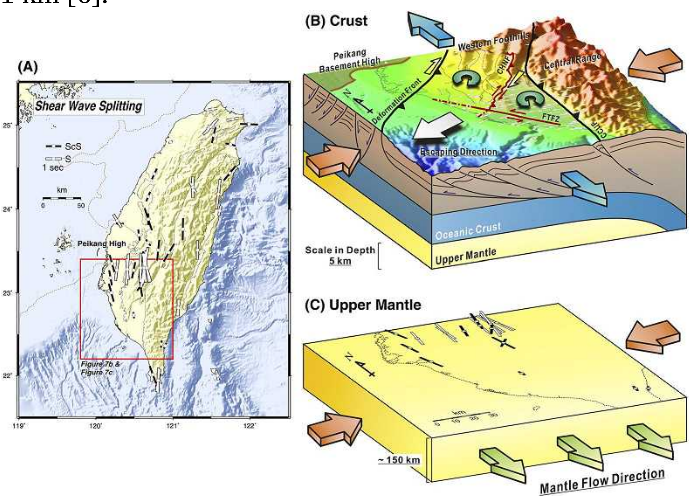

Fig. 3. Tectonic kinematic model of SW Taiwan showing (a) shear wave splitting, (b) tectonic escape model for the crust, and (c) tectonic escape model for the upper mantle. Redrawn from [4, 5]

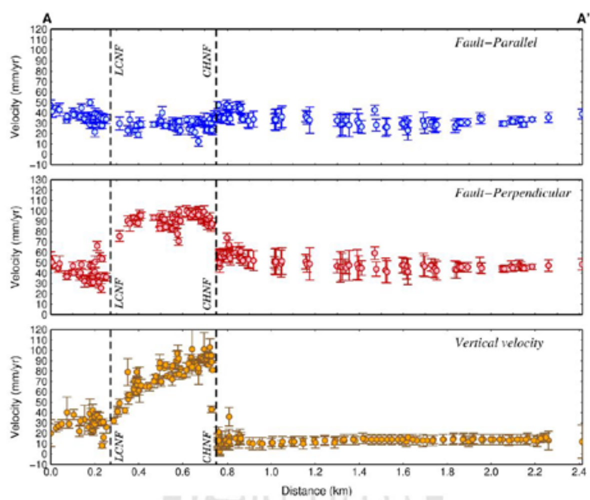

Fig. 4. 3D velocity profiles of (a) fault-parallel, (b) fault-perpendicular, and (c) vertical velocities

2.3 Study of crustal uplift rate and fault evolution for CKNF

The CKNF is the extension of the southern segment of the LCNF. It is suspected that local irregularity of the alignment may be associated with movement of the creeping CKNF. Because no data or research are available to support this hypothesis, a thorough investigation plan, including a geological investigation and monitoring of surface deformation was therefore initiated to verify if the CKNF fault passes through the railway alignment, and to understand its kinematics. Combining the observations from geomorphological characteristics and field investigation, the location of the fault line across the railway alignment was first identified, and then confirmed based on the differences of bedrock composition and bedrock deformation orientation. The results from a geological borehole investigation indicate that the bedrock in the hanging wall has a high dip angle (40-90°) with highly ductile shear zones. However, the dip angle of the bedrock in the footwall is relatively gentle (35-50°) and occasionally interlayered with thin-bedded fault gouge (< 1 cm in thickness). Figure 5 is the geological cross-section showing the estimated fault line location, soil strata, and measured dip angle at different depths. In order to further verify the activity of the CKNF, soil samples were taken to do radiocarbon dating (^{14}C) and nannofossil analysis. The test results indicate that the CKNF has been active since the Holocene, and forming growth strata that allow deformation and deposition of the Holocene marine alluvium to occur simultaneously.

In order to quantify the kinematics of the CKNF since the Holocene, long-term crustal uplift rate (R), is calculated by Eq. (1), with the parameters of the elevation of sample (A), eustatic sea level (B), the depth of paleo environment (C) and calibrated ^{14}C age (cal yr BP).

$$R = (A - B - C) \div (^{14}C \text{ cal yr BP}) \tag{1}$$

The calculated crustal uplift rate suggests that the CKNF has been active over the last 10,000 years. The uplift rate is 3.8±0.9 mm/yr in the hanging wall and 0.4±0.7 mm/yr in the footwall. Figure 6 shows profiles of the long-term uplift rate and the short-term uplift rate measured by a leveling survey on piers of the viaduct structure since 2005. The patterns of long-term and short-term uplift rates are comparable.

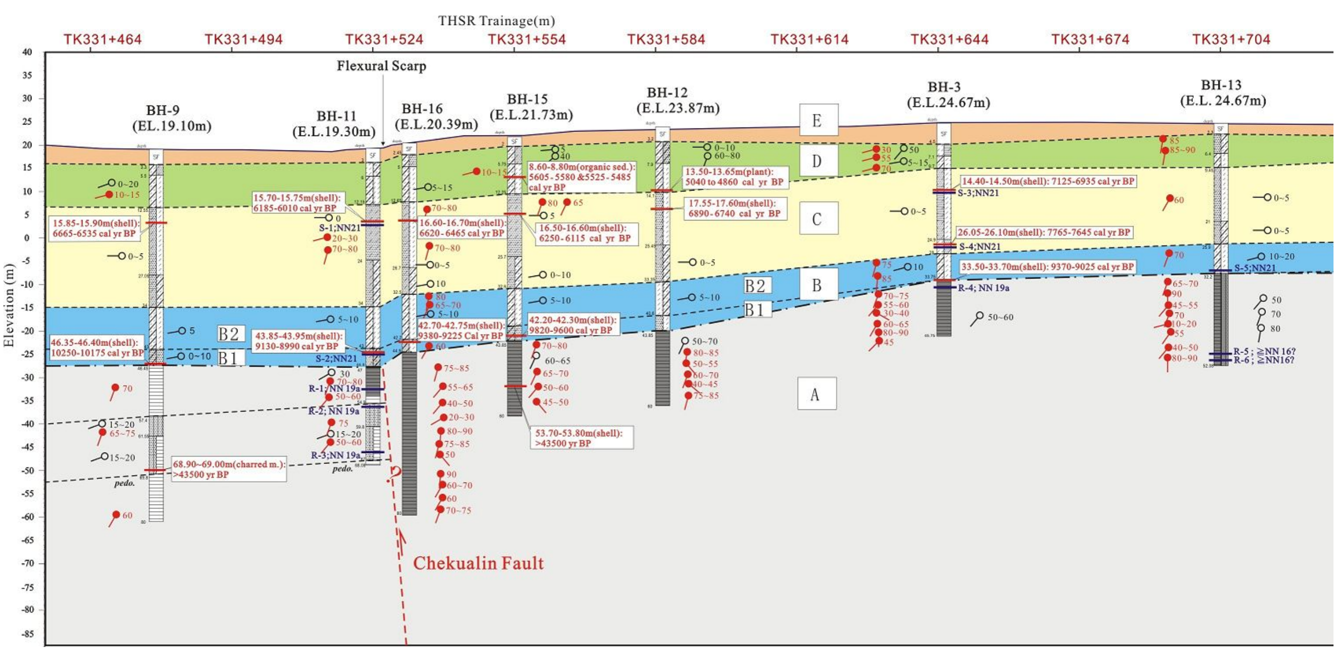

Fig. 5. Geological cross-section of the study area

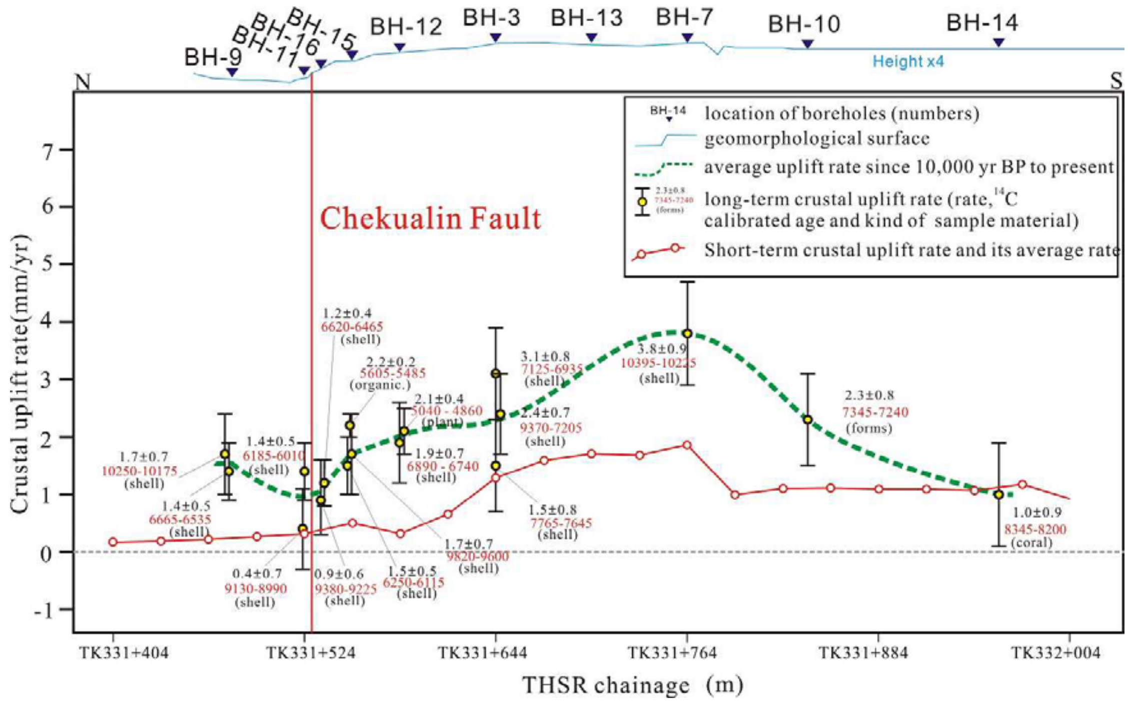

Fig. 6. Long term and short term crustal uplift rates with location of boreholes BH-7 to BH-16 on profile of geomorphological surface at top.

3. Displacement behavior of line-shaped elevated structure

3.1 Monitoring program

A long-term monitoring program was established to monitor ground movement by a leveling survey supported by GPS, and displacement of the elevated structure starting from the bedrock at the base, up to ground level, the pile cap structure, the pier structure, and the deck at the top. The adopted monitoring devices include borehole tilt-meters (Pinnacle 5000) embedded into the bedrock, structure tilt-meters installed on the pile and pier structures, and LVDT sensors to measure the relative movement between the decks. Figure 7 is the layout of the geodetic network composed of GPS stations, leveling benchmarks, and campaign GPS stations to monitor 3D movement of the ground and viaduct structure. Figure 8 is a 3D view of the instrumented viaduct structure to monitor the displacement of the deck, piers, pile caps and ground. The data will provide a deeper insight into the safety of the structural members of the viaduct, such as the piles and piers. The evolution of the alignment dislocation can also be evaluated by the relative movement between decks on the east side and west side.

3.2 Bedrock and pile foundation

The piles were designed and constructed to embed into the bedrock of mudstone to a depth of at least 3 times the pile diameter. In addition to the various load combinations considered in the design, pile structure safety could be affected by the relative movement between the mudstone and the pile cap, and soil movement surrounding the pile structure due to crustal movement. Figure 9 shows traces of the bedrock and pile cap during the 6-month monitoring period. The maximum tilting on a pile cap was around 100 seconds over the 6 month period. In general, tilting on the pile caps during the 6 month period is an order of magnitude greater than tilting on the bedrock. Long term monitoring will be conducted to assess the safety of the pile structures.

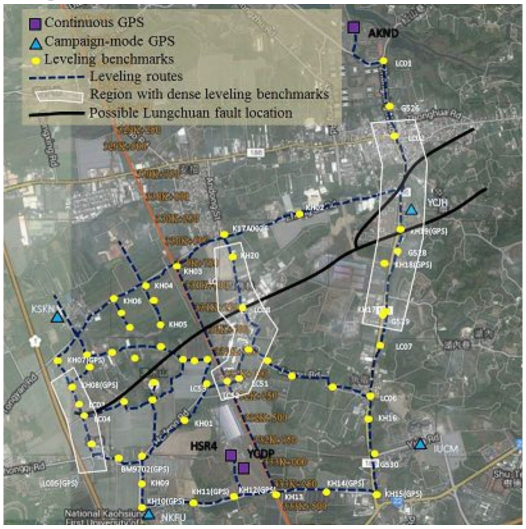

Fig. 7. Geodetic network in the study area

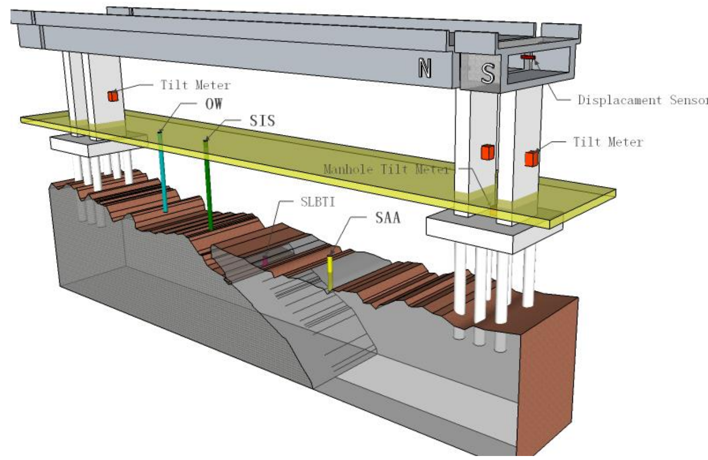

Fig. 8. 3D view of instrumented viaduct structure

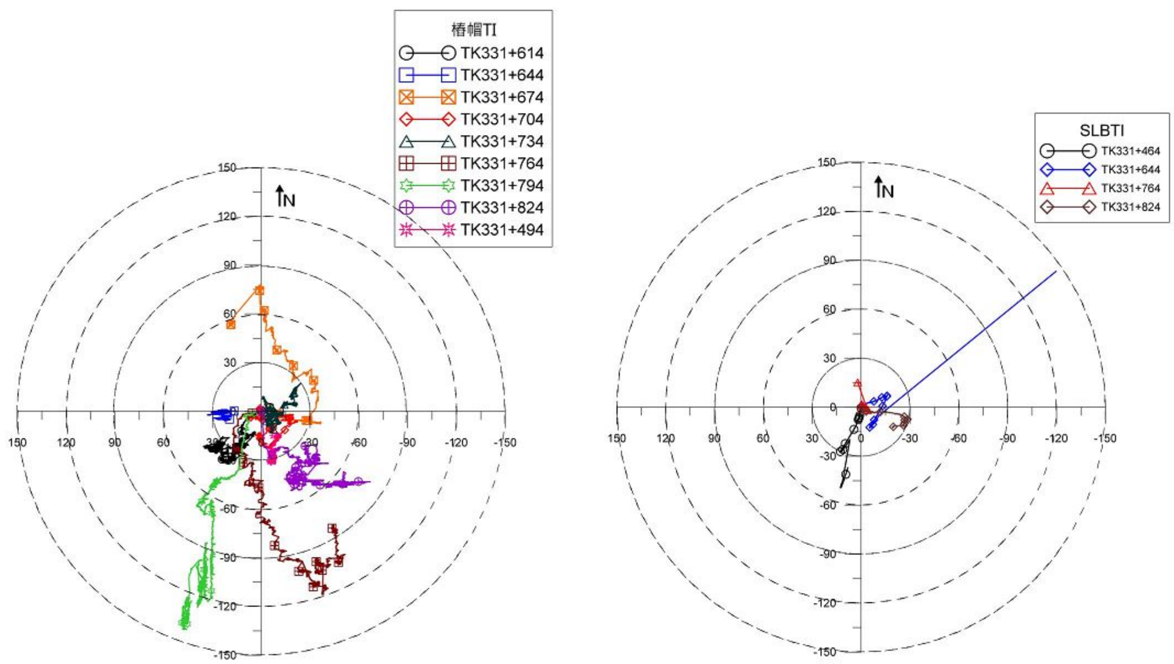

Fig. 9. Traces of movement on the bedrock and pile cap

3.3 Pier structure

The typical type of superstructure consists of double piers seated on the same pile cap and rigidly fixed with box-girders, but without pot bearings. The data from the tilt-meters installed on each pier demonstrate tilting varies with temperature changes but occurs in the longitudinal direction of the alignment. Tilting perpendicular to the alignment is small and can be ignored. Figure 10 shows typical integrated displacement behaviors from piers, pile caps and bedrock during the 6-month monitoring period.

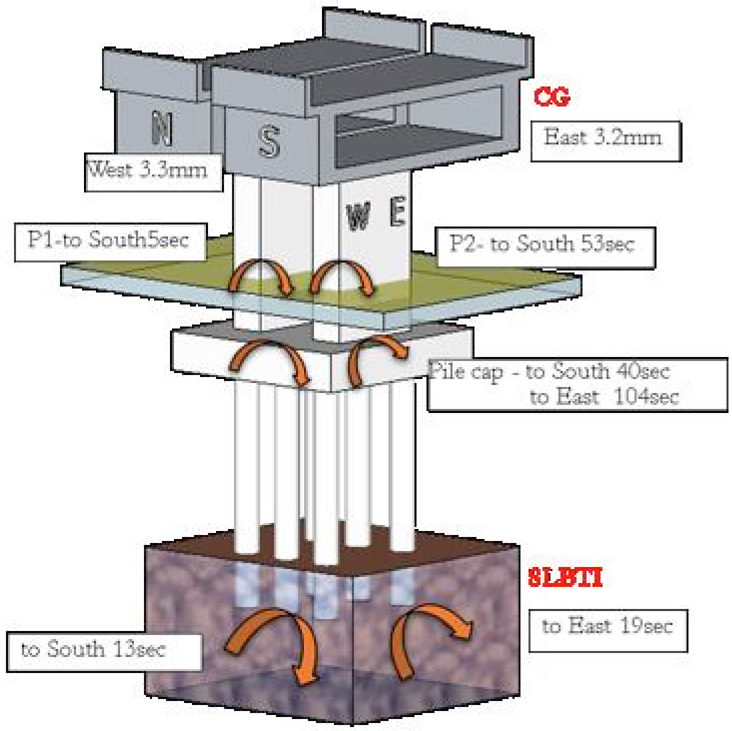

Fig. 10. Typical integrated displacement behaviors among piers, pile caps, and bedrock

3.4 Deck

The LVDT type displacement sensors were installed on the east and west side of the joint between deck sections. The deformed shape of the alignment in the study area was processed using the versine of the relative movement in the EW direction between decks, and is shown in Figure 11. This diagram indicates that there are two critical areas that are suffering dislocation in the alignment. The measurement were taken between 2014/1/20 to 2015/11/25.

4. Conclusions

The displacement of a line-shaped elevated structure caused by long-term crustal movement due to a creeping fault is critical, since it will affect not only the safety of the structural members, but also the alignment regularity. A three-stage work plan was initiated in 2015 that include the geological investigation and monitoring system set-up, safety assessment of elevated viaduct structure subject to crustal movement, and necessary remedial work. The findings from the stage-one work are as blow.

(i) The location of creeping fault, CKNF, across the railway alignment has been identified by the data from geological borehole investigation.

(ii) The studies of radiocarbon dating (^{14}C) and nanofossil analysis demonstrates that the long-term uplift rate of the crustal displacement is 3.8±0.9 mm/yr in the hanging wall and 0.4±0.7 mm/yr in the footwall of the CKNF conforming to the pattern of short-term uplift rate measured by a leveling survey on the elevated structure since 2005.

(iii) Considering the displacement across the creeping fault is cumulative, and will last for the entire design life of the infrastructure, one comprehensive, long-term monitoring system has been built up in order to integrate the displacement behaviors of the elevated viaduct structure system from the deck, piers, piles, and down to the bedrock. The data from the last 6-month monitoring period demonstrates that the movement of elevated superstructure could be related to the movement of bedrock. However, the 6-

month monitoring period is too short to capture the trend of displacement interaction between elevated structure and crustal movement in the study area.

A database will be built-up by the effort of long term monitoring to comprehend the interactions among bedrock, ground, pile, pier, and viaduct deck that can support the assessment of structural capacity check for the elevated viaduct structure subject to crustal movement under different loading combinations specified in original seismic design.

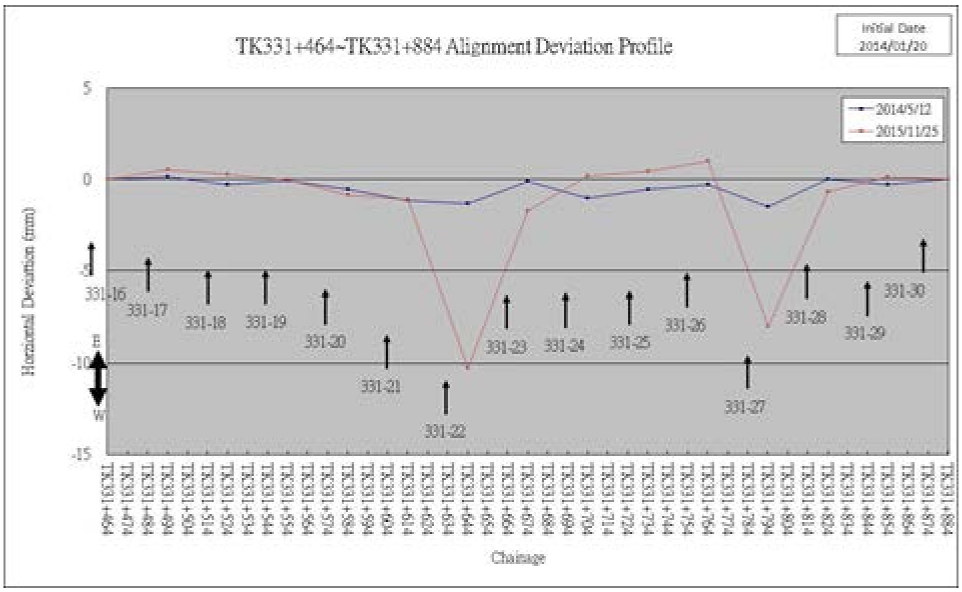

Fig. 11. Deformed shape of the alignment in the study area

5. Acknowledgements

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6. References

[1] Suppe, J. (1984): Kinematics of arc-continent collision, flipping of subduction, and back-arc spreading near Taiwan, *Memoir of the Geological Society of China*, 6, 21-33.

[2] Yu, S.B., Chen, H.Y., Kuo, L.C. (1997): Velocity field of GPS stations in the Taiwan area. *Tectonophysics*, 274, 41–59.

[3] Lu, C.Y., Jeng, F.S., Chang, K.J., Jian, W.T. (1998): Impact of basement high on the structure and kinematics of western Taiwan thrust wedge: insights from sandbox models. *Terr. Atmos. Ocean Sci.* 9, 533–550.

[4] Ching, K.E., Rau, R.J., Lee, J.C., and Hu, J.C. (2007): Contemporary deformation of tectonic escape in SW Taiwan from GPS observations, 1995-2005, Earth and Planetary Science Letters, 262, 601-619.

[5] Ching, K.E., Hsieh, M.L., Johnson, K.M., Chen, K.H., Rau, R.J., Yang, M. (2011): Modern vertical deformation rates and mountain building in Taiwan from precise leveling and continuous GPS observations, 2000-2008, *Journal of Geophysical Research,* 116, No. B08406, doi:10.1029/2011JB008242.

[6] Yang, M., Ching, K.E., Lee, C.C., Chen, Y.S., Cheng., S.C. (2015): Monitoring and predicting the behavior of the Lungchuan and Chishan faults with GNSS, *Proceedings of the ION 2015 Pacific PNT Meeting*, April 20-23 2015, 536-541.