# RECENT SURVEY RESULTS OF THE SUPERKEKB MAIN RING AND THE STUDY OF ATL APPLICATION

M. Masuzawa†, S. Nakamura, Y. Ohsawa, R. Ueki, KEK, Tsukuba, Japan

*Abstract*

SuperKEKB is a double-ring collider featuring a 7 GeV electron ring (HER) and a 4 GeV positron ring (LER), with a circumference of 3 km [1,2]. It was constructed by repurposing the KEKB tunnel, which was decommissioned in 2010. At the time of construction, the KEKB beamline magnets were aligned within the same plane. SuperKEKB employs a "nano-beam scheme," wherein two low-emittance beams collide at a crossing angle of 83 mrad at the interaction point (IP). Compared to KEKB, SuperKEKB is more sensitive to machine errors, such as misalignment. To achieve higher luminosity, it is essential to compensate for distortions in the closed orbit and optical functions caused by tunnel subsidence. Approximately 200 level reference points, spaced roughly evenly along the 3 km tunnel, are surveyed each year during the summer shutdown period using the Wild N3 precision level.

An empirical ATL law [3,4] describes the relative displacement of two distant ground points as products of a site-dependent ground diffusion coefficient *A,* a temporal survey span *T*, and spatial scales *L*. This ATL law is applied to the SuperKEKB level data collected from 2004 to 2024, allowing for the determination of the coefficient *A*. The new survey results and the study of ATL applications are reported herein.

## INTRODUCTION

SuperKEKB was constructed by repurposing the tunnel of its predecessor, the KEKB. Figure 1 illustrates a geological columnar section along the KEKB/SuperKEKB tunnel, obtained from a boring survey. It is evident that at the KEK site, even when excavating to a depth of 100 m, the bedrock line is not encountered. The arc sections of the SuperKEKB Main Ring (MR) tunnel are founded on a gravelly diluvial layer located 12 m below ground level (GL). The basement floors of the four experimental halls—TSUKUBA, OHO, FUJI, and NIKKO—are situated 16 meters below GL. Since this depth comprises a diluvial clay stratum, the experimental buildings were constructed on pile foundations. The underside of the concrete floor of the experimental hall lies 20 m below GL and is supported by piles with diameters ranging from 1.2 m to 1.4 m and a length of approximately 20 m, which extend down to the gravelly layer. The four straight sections connecting the arc sections to the experimental buildings are also built on pile foundations. Expansion joints are incorporated every 50–60 m in both the arc and straight sections to accommodate the thermal expansion and contraction of the concrete.

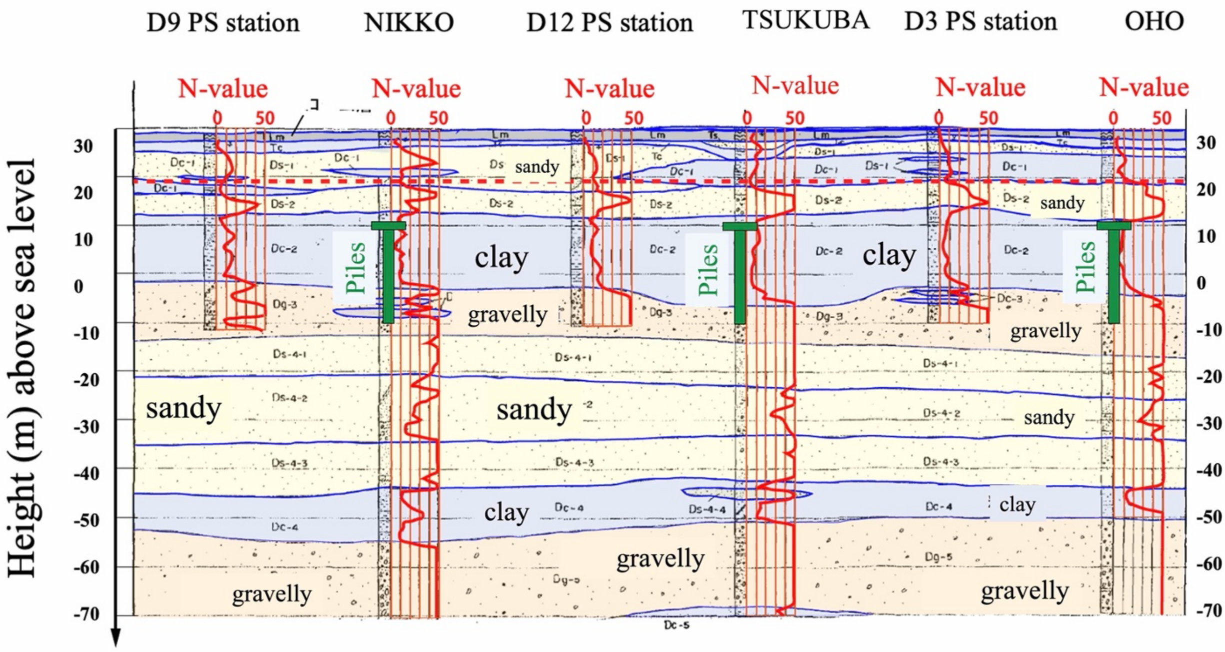


Figure 1: Geological columnar sections along the KEKB/SuperKEKB tunnel, obtained from a boring survey. The green bars indicate the locations of the piles.

† mika.masuzawa@kek.jp

Over the years, the southern part of the tunnel has experienced subsidence, leading to the readjustment of the tunnel-level reference monument to a level surface in 1998, at the onset of KEKB's construction.
The construction of SuperKEKB started in 2010, and despite the Great East Japan Earthquake in 2011, beam commissioning began in February 2016. Due to the extremely tight construction schedule, the installation, surveying, and adjustment of the magnets for SuperKEKB were carried out concurrently with the construction of the utility building for the new power supply and water supply systems, located above ground near the tunnel. Additionally, a few meters above the SuperKEKB tunnel, work was underway on a new beam transport line that would connect to another accelerator facility (PF-AR). Construction of this facility began in 2013 and involved the excavation of a vertical access shaft immediately adjacent to the tunnel, as indicated in Fig. 2.

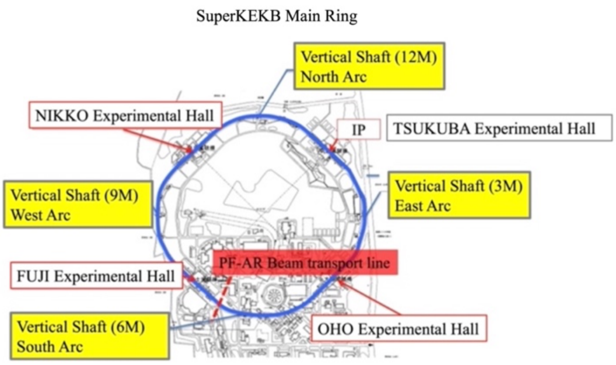


Figure 2: New utility buildings were constructed, and vertical access shafts were excavated alongside the SuperKEKB tunnel. Simultaneously, a new PF-AR beam transport (BT) line was built directly above the SuperKEKB tunnel.

This large-scale construction project has not only complicated the establishment of a new survey network for magnet alignment but has also significantly impacted ground motion around the tunnel. These "systematic" movements are not anticipated to conform to the diffusive characteristics described by the ATL law. The changes in tunnel level before and after the construction in 2013 were plotted against *s*, defined as the distance measured counterclockwise from the interaction point (IP) when viewed from above the KEKB tunnel, as illustrated in Fig. 3. Very clear effects of excavation are evident.

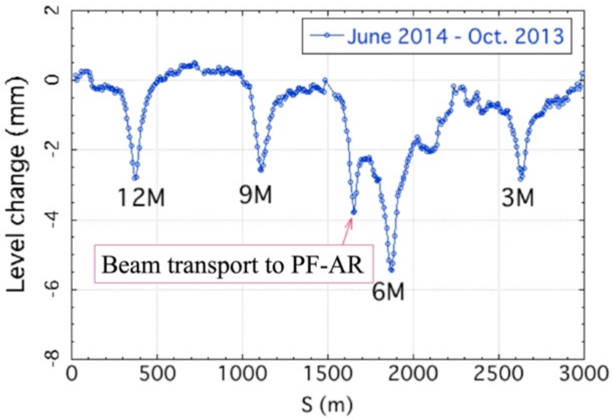


Figure 3: Comparison of tunnel level changes before and after the utility construction. The labels 3M, 6M, 9M, and 12M correspond to the newly excavated vertical shafts.

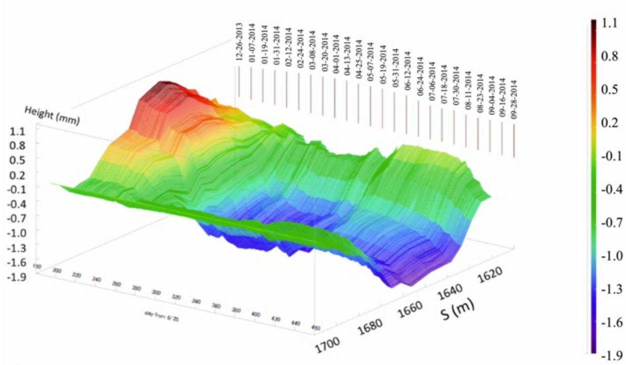


Figure 4: Effects of the excavation of the PF-AR tunnel as monitored by the HLS system.

Floor motion was monitored during the construction of the PF-AR BT line using the HLS system, as depicted in Fig. 4, between s = 1600 m and s = 1700 m. The tunnel level does not appear to have returned to its original position prior to construction. The effects of various construction activities persist even after 10 years, as described in the following section.

## LEVEL DATA FROM 2004 TO 2024

Tunnel-level surveys have been conducted every summer during KEKB operation, throughout SuperKEKB construction, and after SuperKEKB operation commenced in 2016. The tunnel level relative to the IP surveyed during the summer shutdown period is plotted against *s* in Fig. 5 for the years 2004 to 2024. The data for 2011 and 2012 are not included in Fig. 5, as surveys were conducted irregularly following the earthquake. The changes in levels between 2004 and 2005, as well as between 2013 and 2014, were more pronounced. The significant fluctuations observed in 2013 and 2014 can be attributed to multiple construction projects near the tunnel; however, the cause of the substantial fluctuations in 2004 and 2005 remains unknown. No major construction projects were undertaken during this period, and KEKB was operating normally.

The area that has experienced the most significant change and subsidence over the past 25 years is between *s*=1700 m and *s*=1800 m. As of 2024, the amount of subsidence has exceeded 40 mm, which corresponds to a sinking rate of over 1.5 mm/year at the lowest point of the MR. The subsidence around the IP and the straight sections on either side of the IP is less pronounced than in the other arc sections of the MR. This reduced subsidence is attributed to the experimental halls being built on pile foundations, which have proven effective.

At this stage, the impact of this level of subsidence on the performance of SuperKEKB, particularly regarding the deterioration of vertical emittance, remains within acceptable limits [5]. However, some countermeasures may be necessary in the future to achieve the designed emittance of SuperKEKB. No trend indicating a halt in tunnel subsidence has yet been observed. The movement of the tunnel is strongly influenced by the differing supporting structures and by the various construction activities carried out at multiple locations, as described above.

Figure 6 illustrates the yearly changes in the elevation of the surveyed reference marker points by tunnel section. Significant fluctuations were observed in the arc sections, which are installed directly in the ground without a piling structure. These fluctuations were notably more pronounced in 2013 and 2014, coinciding with construction activities at various locations along the tunnel. Among the four experimental halls, those located on the northern side of the MR—Tsukuba and Nikko—exhibit less variation than the other two halls. The reason for the differences between the four experimental halls, despite being built using similar pile foundation methods, is not clearly evident from Figure 1 alone. It is suspected that local geology and groundwater conditions may play a significant role.

It remains uncertain whether the amount of level change is gradually decreasing post-construction. The possibility that the long-term effects of the earthquake are still present cannot be ruled out.

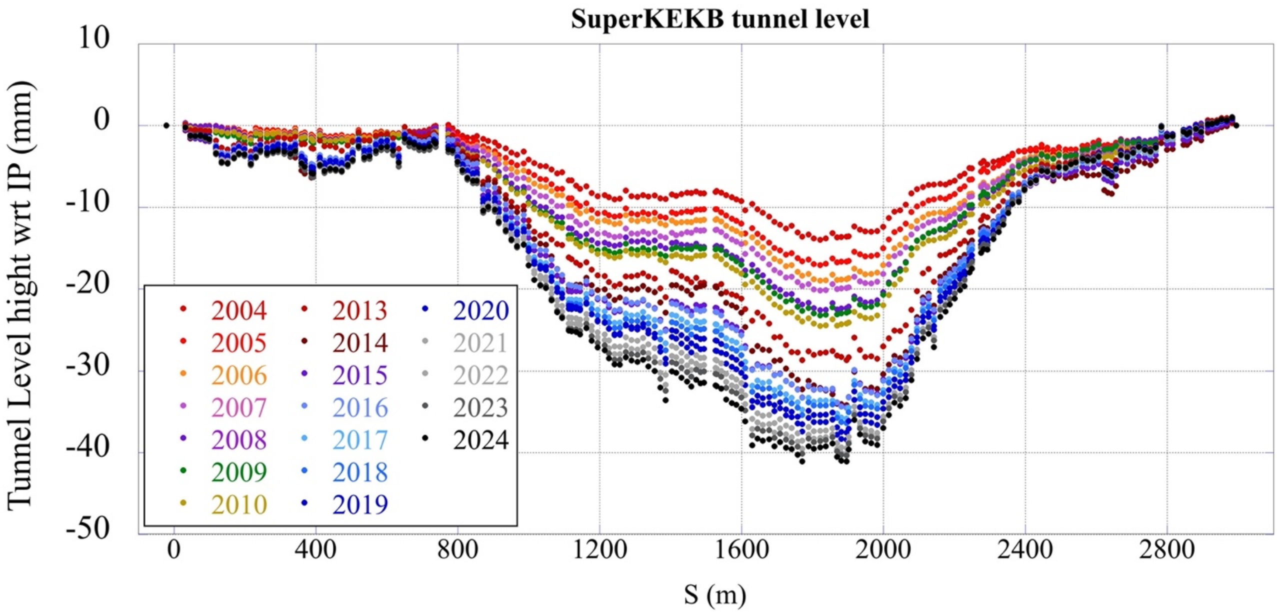


Figure 5: Tunnel level relative to the IP is plotted against *s*, the distance from the IP measured counterclockwise. The data presented in this plot were obtained from the level marker surveys conducted during the summer shutdown periods. The data for 2011 and 2012 are excluded from this plot, as those surveys were conducted in February and March.

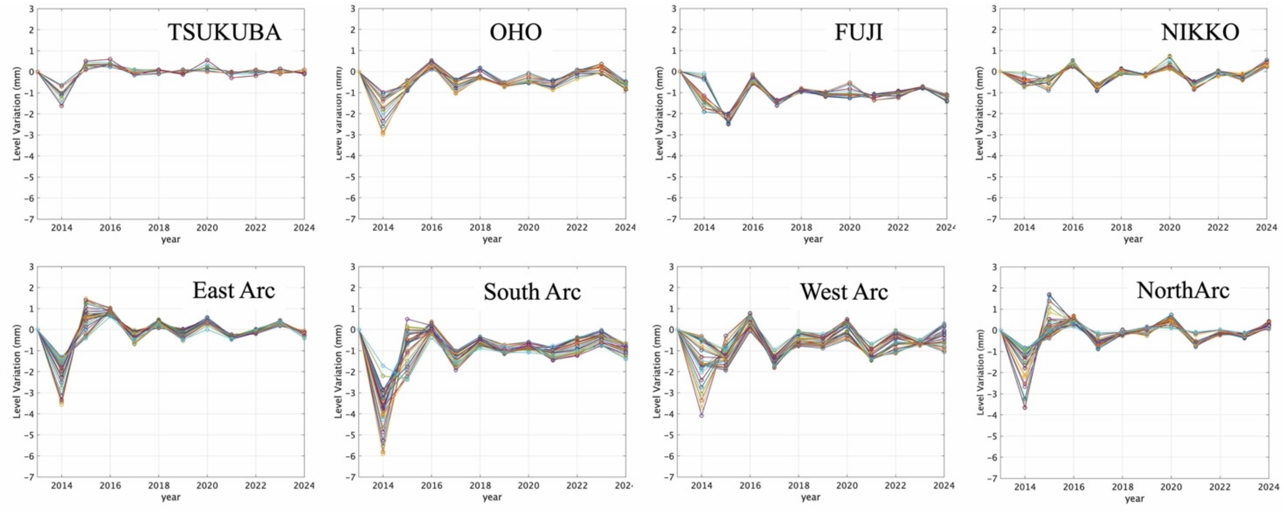


Figure 6: Tunnel level changes per year are plotted for each reference level marker from 2013 to 2024 for different sections of the tunnel, as depicted in Fig. 2. The sections where the experimental halls are located exhibit less level variation compared to the arc sections. The effects of the excavation work in 2013 and 2014 persisted into 2015 and possibly 2016.

## TRIAL OF ALT LAW APPLICATION

An attempt was made to apply the empirical ATL law, which expresses the variance $\langle dz^2 \rangle$ of the height difference of the ground over a time interval $T$ between two points separated by a distance $L$, as shown in Eq. (1), with both exponents close to 1 ($\alpha \sim 1,\ \beta \sim 1$) [3,4], to the results of the level survey of the SuperKEKB tunnel. The coefficient $A$, referred to as the "ground diffusion coefficient," depends on the characteristics of the soil of the site. These characteristics were summarized by V. Shiltsev for various accelerator sites [3,4].

$$\langle dz^2 \rangle \approx AT^{\alpha} L^{\beta} \qquad (1)$$

The variance of the tunnel level changes was calculated using the following equation [6], where $M$ and $N$ represent the number of combinations of pairs of time intervals $T$ and tunnel level marker points, respectively, separated by $L$ [6]:

$$\langle dz^2(T,L) \rangle = \frac{1}{M} \sum_M \frac{1}{N} \sum_N \{dz(T, s+L) - dz(T,s)\}^2 \qquad (2)$$

### *SuperKEKB data*

The slope of the variance in the level change for each time interval was evaluated and plotted in Fig. 7 for the case where $0 < L < 140\ (m)$, using data from 2004 to 2010 (prior to the earthquake and various construction works) and data from 2014 to 2024. The coefficient of the empirical ATL law, which characterizes the geological features, is estimated as $A = 0.50 \pm 0.19\ /\ mm^2\ /\ km$ and $A = 1.09 \pm 0.15\ /\ mm^2\ /\ km$ for the survey data from 2004 to 2010 and from 2014 to 2024, respectively. The coefficient $A$ is larger after the earthquake and construction, suggesting that the ground subsidence may not have fully settled following the earthquake and/or the excavation work.

All data from 2004 to 2024 were combined and plotted in Fig. 8. Data spanning both periods, such as from 2008 (before the earthquake) and 2016 (after the earthquake), were excluded as a measure of change over eight years. This exclusion is due to systematic factors influencing changes between these two periods, such as the earthquake and construction activities along the tunnel.

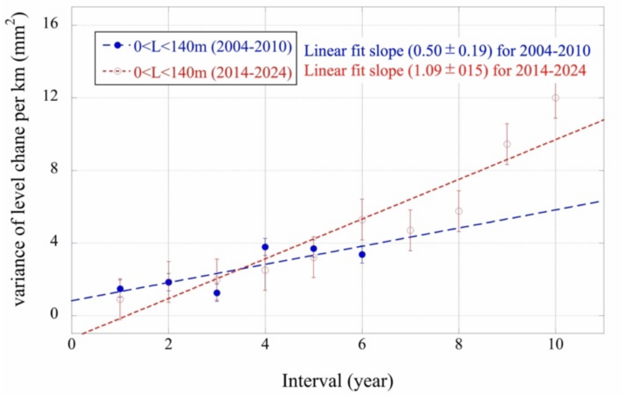


Figure 7: Variance of level change per unit distance (km) is plotted against the survey interval. The data is divided into two periods: 2004 to 2010, prior to the earthquake and large-scale construction, and 2014 to 2024, following these events.

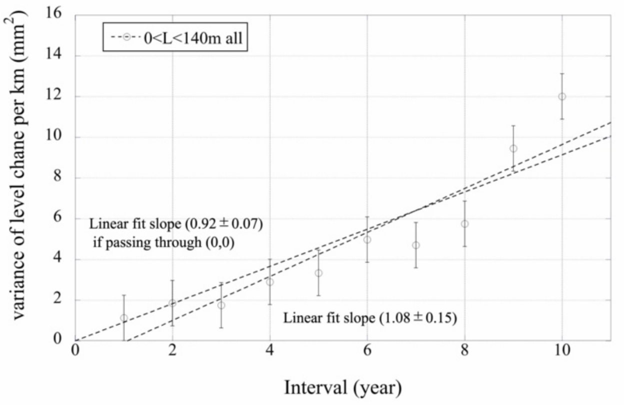


Figure 8: Variance of level change per unit distance (km) is plotted for $0 < L < 140\ (m)$against the survey interval. All data from 2004 to 2024 are combined in this analysis.

The combined data result in $A = 1.08 \pm 0.15\ /\ mm^2\ /\ km$ and $A = 0.92 \pm 0.07\ /\ mm^2\ /\ km$ when the data are fitted with a linear function and a linear function passing through the origin, respectively. Figure 9 presents a plot similar to that in Fig. 8, but with a narrower analysis range where $0 < L < 99\ (m)$. The obtained coefficient is consistent with that obtained for $0 < L < 140\ (m)$. If the analysis range o $L$, is extended further, the systematic movements of tunnel subsidence become more pronounced, exceeding the applicability of the empirical ATL analysis.

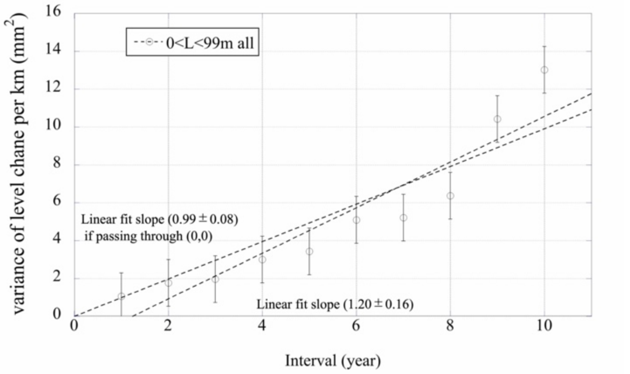


Figure 9: Variance of level change per unit distance (km) is plotted for $0 < L < 99\ (m)$ against the survey interval. All data from 2004 to 2024 are combined in this analysis.

### *Comparison with other sites*

Some of the coefficients obtained and summarized by V. Shiltsev et al. [3,4,6] are presented in Table 1 for comparison with the SuperKEKB data. The SuperKEKB coefficient derived from this analysis was converted into the units used in the references. The DL in Table 1 corresponds to the spatial scale, representing the length covered by the HLS system at LEP, CERN SPS, and TEVATRON, as well as the length used for linear fitting of the variance in the level-change data at SPring-8 and SuperKEKB. It is not surprising that the diffusion coefficient for SuperKEKB is larger than that of other accelerator facilities, as the ground at the SuperKEKB construction site is known to be softer and more saturated with groundwater than at other accelerator sites.

Table 1: Diffusion coefficients for vertical plane diffusion at various accelerator sites.

| Site | A $10^{-6}\mu m^2/s/m$ | Time | Comments |
|---|---|---|---|
| LEP | 3 ± 0.6 | 6 yrs | ΔL = 39m |
| CERN SPS [3,4] | 14 ± 5 | 3-12 yrs | ΔL = 32m |
| TEVATRON [ 3,4] | 4.9 ± 0.1 | 1-6 yrs | ΔL = 30m |
| SPring-8 [6] | 7.6 ± 1.4 | 20 yrs | ΔL ~ 400m |
| SuperKEKB | (29~34) ± ~5 | ~10 yrs | ΔL ~ 140m |

## CONCLUSION

Tunnel-level survey data from 2004 to 2024 have been summarized and presented. The southern arc section of the SuperKEKB MR continues to sink, with the relative amount of subsidence with respect to the IP exceeding 40 mm. Currently, there are no indications that the tunnel subsidence has ceased; if this trend continues, the relative subsidence could reach 50 mm by 2030.

This study marks the first attempt to apply the empirical ATL law to the tunnel deformation of the SuperKEKB MR. Several factors may have contributed to systematic ground deformation, including the use of different construction methods for the SuperKEKB tunnels, the occurrence of a major earthquake just before construction, and extensive excavation work around the MR after SuperKEKB's construction began. For this reason, we analyzed the data separately for the period before the earthquake and during the construction phase, while limiting the spatial scale to approximately 150 m. Consequently, we obtained a diffusion coefficient that is several to ten times larger than those of other accelerators, which was somewhat anticipated given that the ground at the KEK site is softer than at other locations.

The ATL law was applied in the vertical direction, specifically to the variation in tunnel-level marker changes. Future efforts will focus on applying the law in the horizontal direction, examining variations in the circumference.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance of their colleagues in the SuperKEKB magnet group. Special gratitude is extended to Dr. Y. Okayasu for his constructive suggestions regarding the analysis.

## REFERENCES

[1] M. Masuzawa, "Next Generation B-factories", Proceedings of the 1st International Particle Accelerator Conference (IPAC10), Kyoto, May 2010.

[2] K. Akai et al., "SuperKEKB Collider", NIM A, vol. 907, pp. 188-199, 2018.

[3] V.D. Shiltsev, “Observations of random walk of the ground in space and time”, Phys. Rev. Lett. 104 (2010) 238501.

[4] V.D. Shiltsev, “SPACE-TIME GROUND DIFFUSION AND ITS FRACTAL NATURE”, 0FERMILAB-FN-0834-APC (FNAL, 2009), arXiv:0905.4194

[5] A. Morita, “Estimation of Tunnel Subsidence Effect on SuperKEKB”, 9th Annual Meeting of PASJ, Osaka, August 2012, THPS028, p. 930 (2012)

[6] Y. Okayasu et al. “An interpretation of Spring-8 ground elevation by the empirical ATL-law approach”, JINST 15, P03033, 2020