Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

Record of long-term field observation of large-scale cutting slope

Shotaro Hijikata[1], *Reiko* Kuwano[2], and *Hirotake* Nakamura[3]

[1]*The University of Tokyo, Department of Civil Engineering, 7-3-1 Hongo Bunkyo-ku Tokyo 113-8656, Japan*
[2] *The University of Tokyo, Institute of Industrial Science, 4-6-1 Komaba Meguro-ku Tokyo 153-8505*
[3]*Central Nippon Expressway Company Limited, 2-18-19 Nishiki Naka-ku Nagoya 460-0003*

ABSTRACT

This paper describes the interpretation of landslide behavior and verification of the effectiveness of countermeasure works based on the results of long-term field observations at a large-scale cutting site. The site has been subjected to various deformations since its construction due to its unique geological conditions, and has been monitored extensively by GPS surface displacement gauges, borehole inclinometers, anchor load cells, and water level gauges as an important monitoring site even after it was put into service. In the sixth year after the site was opened to public use, we assumed underground slip surfaces based on an interpretation of the observed data, constructed additional countermeasures, and verified the effectiveness of the countermeasures through continuous field observation of intermittent landslide behavior observed in several areas of the slope. As a result, it was confirmed that the displacement had not been settled even five years after the construction of the additional countermeasures and that a new slip surface had emerged, indicating the necessity of improving field observation techniques and data interpretation as well as continuous monitoring of this site.

Keywords: long-term field observations; large-scale cutting slope; countermeasures.

1. Introduction

Maintaining the functionality of social infrastructure is essential for active social activities and disaster prevention and mitigation. Detecting structural deformations from the initial minute stage and promoting preventive maintenance is necessary to maintain sound infrastructure. For this purpose, remote monitoring using measuring instruments is now widely used as a general maintenance management method for structures.

As an example of such monitoring, this paper describes the detailed analysis of slope changes and the effectiveness of countermeasures based on the results of various previous monitoring activities at site A, located on a road in Japan. The road facing site A is one of Japan's most heavily trafficked arterial roads, and proper maintenance and management of the soil structure is highly important. However, due to its unique geological conditions, displacement has occurred intermittently from construction to the time the road is in service, and detailed field monitoring has been conducted for more than ten years. As a case study of applying geotechnical engineering theory in monitoring methods and interpretation of observed data, we present the results of these observations and the process of studying countermeasures. This paper is written based on the internal reports of NEXCO Central Ltd[1].

2. Site Descriptions

Fig. 1 shows a panoramic view of site A in Japan, the site of this measurement. The slope was designed with a 1:1.8 slope for the upper three levels and a 1:2.8 slope for the lower three levels, and this section was constructed from 2005 to 2012. According to the geological map, the strata around the site are mainly composed of sedimentary rocks such as mudstone and conglomerate, and the slope of site A is a dip slope (Fig. 2 and 3). The results of the construction borings also confirmed this.

Fig. 4 shows a summary of each monitoring device's location on the drawing of site A. Based on the results of other cut slope construction projects that had started nearby before this project, the overall slope was made more gradual than in the initial design, and additional countermeasures were constructed at each cut stage by repeatedly modifying the design as conducting test cuts and field observations in the construction process.

Figure 1. Panoramic view of the measurement site A (on the right side), taken just before the start of service (2012).

At the time of the opening to service, we implemented the following countermeasures: ground anchor work (partly with framework), drainage borings, water collection wells, cast-in-place concrete retaining piles, pile-head ground anchor work, and reinforced cut slope. Since the start of service, on-site field observation has been conducted using GPS surface displacement gauges, borehole inclinometers, anchor tensile load cells, and groundwater level gauges. The slope still has deformations that need to be resolved even after it was opened for public use.

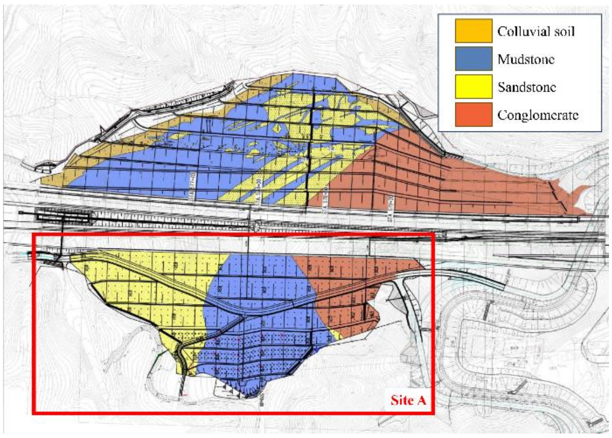

Figure 2. Geological map of site A (along slope).

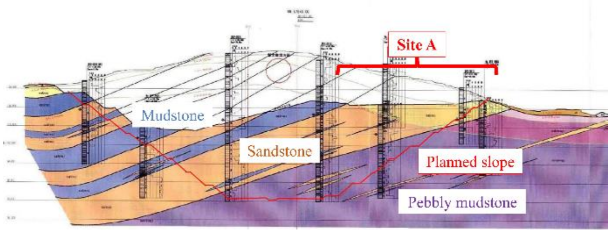

Figure 3. Geological map of site A (cross-section).

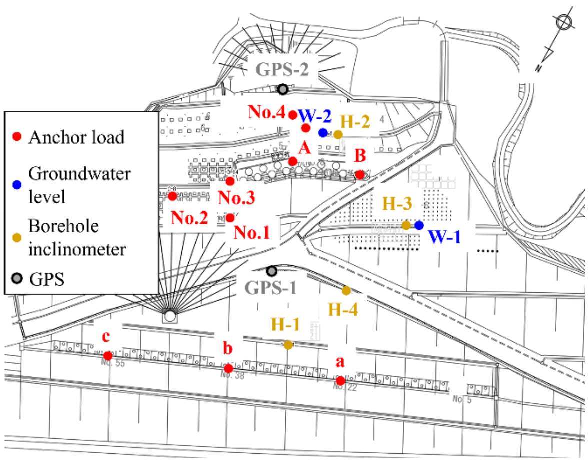

Figure 4. Overall drawing of the site and monitoring points.

3. History of field observation and countermeasures

Fig. 5 shows the main countermeasures being constructed at site A. The countermeasures indicated in blue were in place when the site was opened for service in 2012, including two water collection wells on the upper and lower east sides of the slope, ground anchors on the middle east and upper sides, cast-in-place concrete retaining piles plus their head anchors in the middle center, and steel pipe piles on the lower side. Those shown in red are additional countermeasures constructed in 2019 to counteract landslide fluctuations occurring after the service started. Ground anchors are located on the west side of the upper middle section, and steel pipe pile works on the west side of the middle section; in 2020, a slice cut was done in the lower part of the slope due to the widening of the main road, and pile-head ground anchor works were simultaneously installed on the lower steel pipe piles. These are shown in yellow (fig. 5).

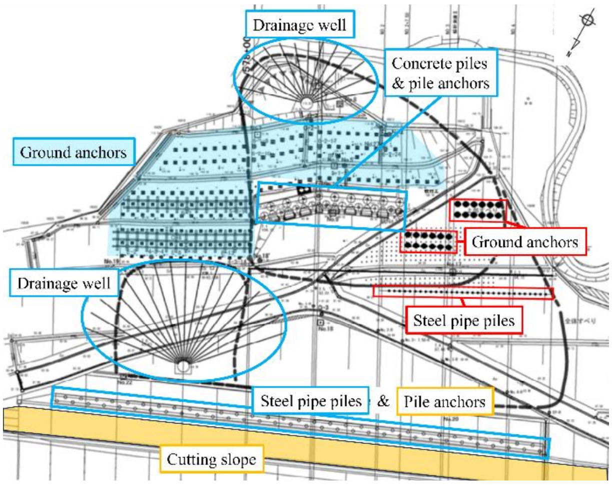

Figure 5. Schematic of countermeasure works.

The deformations and slip surfaces estimated in 2017 are shown in Fig. 6. Surface deformations were visually observed over a wide area of the slope, and four patterns of slip surfaces were inferred to exist: upper slip, overall slip, lower slip, and small-scale slip.

An overview of the deformation conditions at site A as of 2017 revealed many longitudinal cracks in the waterway above the cast-in-place concrete piles and pushing out of the concrete at the top of the waterway on the 1:2.8 slope below the piles (Figs. 7 and 8). The cracks were observed on the west slope and above the steel pipe piles. The longitudinal cracks in the waterway occurred at the head of the center of the landslide, and the pushing phenomenon occurs at the toe of the slope. Based on the distribution of these deformations and the results of field observations, landslide blocks in 2017 were classified as the upper and overall slips. Furthermore, upon inspection, it was found that there were joint openings on the side road situated at the center of the slope and cracks in the mortar spraying on the slice-cut slope due to squeezing (Figs. 9 and 10). Based on the observed distribution of these deformations and field observations, it was concluded that the lower slip occurred between the upper and lower piles. The joint opening on the side road was estimated to be the start of a slip line, while the pushing was the end. Small-scale slides, producing minor deformations, were not included in this study.

Table 1 summarizes the conditions of the upper slip and the overall slip. The lower slip is excluded from the table since it is still under investigation.

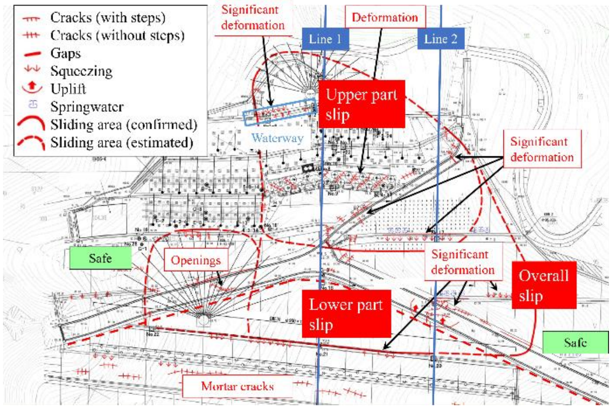

Figure 6. Schematic of landsides and deformations.

Table 1. Estimated conditions of the slips

	Upper slip	Overall slip
Width [m]	80	100
Length [m]	65	100
Depth [m]	15	15~22
Slope surface Gradient [deg]	20~25	10~25
Slip surface Gradient [deg]	5	10
Soil type	Mudstone	Mudstone

Figure 7. A vertical crack along the mortar joint of the waterway at the upper part of the slope.

Figure 8. A waterway block subjected to squeezing at the lower part of the slope.

Figure 9. Joint cracks on the side road.

Figure 10. Cracks of the mortar sprayed slope at the lower part of the slope due to squeezing deformation.

3.1. Results of field observations by 2017

Site A exhibited significant deformations since its opening, prompting ongoing field assessments as it was considered as one of the critical management sites. Consequently, it was determined that stabilization measures had to be implemented by 2017, with further countermeasures under consideration.

3.1.1. Upper slip

In 2017, researchers observed longitudinal cracks in the small steps of the slope surface across the entire area. These cracks were severe in some places, with openings and steps in the repair mortar. Interestingly, the repaired concrete did not show cracks in the middle section. Tensile cracks were also found in the vegetated area near the landslide head, and numerous cracks were observed on the mortar-sprayed surface where reinforcing steel bars were installed on the west side. The extent of the upper slip was hard to estimate only from small cracks at the top of the cast-in-place concrete piles. However, when observing the area between the ground-anchored shotcrete area and the cast-in-place concrete piles on the east side, cracks were found on the slope, which was estimated as the eastern lateral part. The upper slide ended at the point where the gradient changed between 1:1.8 for the upper slope and 1:2.8 for the lower slope. On the west side, there was significant pushing-out and uplift of the top of the channel concrete, which had a large amount of spring water, even during periods of low rainfall. Fig. 11 shows the observation results of water level gauges W-1 and W-2, which always displayed high water levels with minor fluctuations due to precipitation.

On inspection of the cast-in-place concrete retaining piles in the middle section's center, we observed multiple cracks at the top edge of the connecting concrete beam of the pile-head ground anchors and at a small section of the slope surface. The hairline cracks, measuring 1 mm or less, were oriented longitudinally at the top edge of the pile-head connecting concrete. The load had changed at pile-head anchors A and B (fig. 4), as demonstrated in Fig. 12(a) and (b), indicating a continuous increase. While hairline cracks were present in 2011, prior to the installation of pile-head anchors, the number of cracks had risen, and some appeared fresh, indicating that the deformations cause continuous increase in anchor loads. If the trend of the anchor load changes continued, it was calculated that it would take seven years for anchor A and 15 years for anchor B to reach 90% of the yield load, which was the emergency system standard value. Thus, it was necessary to remove the load from the pile-head anchors. The manager of this cut has established a response category when monitoring the displacement and load gauges, which is indicated by the yellow and red lines in the graph. If the tensile force exceeds the yellow line, observation data are examined. If they progress to the red line, the preparation of countermeasures is considered. If the load reaches the red line, countermeasures are implemented urgently such as counterweight fills.

In terms of the ground anchor load gauges near the cast-in-place concrete piles, we noted that there were anchors, such as No. 1 and 4 (Fig. 4) in Fig. 12(c) and (d), where the load tended to increase, while other anchors, such as No. 2 and 3 in Fig. 12(e) and (f), showed no problematic variation. This observation indicates the boundary of the slip surface.

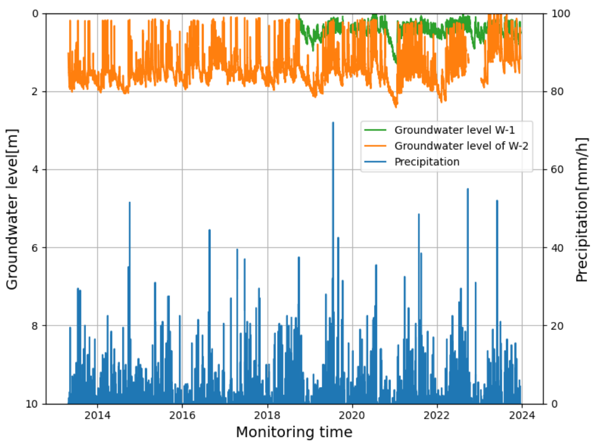

Figure 11. Groundwater levels of W-1 and W-2 and precipitation. W-1 began to be measured in 2018.

Observation results for GPS-2 displacement next to the upper water collection well and water level gauge W-2 (Fig. 4) are presented in Fig. 13(a)~(c). The slope surface near GPS-2 was observed to continue sliding in the road direction. The displacement trend remained consistent and unaffected by the groundwater level (Fig. 13(d)). In Fig. 13(e), changes in borehole inclinometer H-2 observations from 2012 to 2017 are summarized. A continuous increase in displacement was observed from 16m below the surface, which is believed to be the slip surface depth.

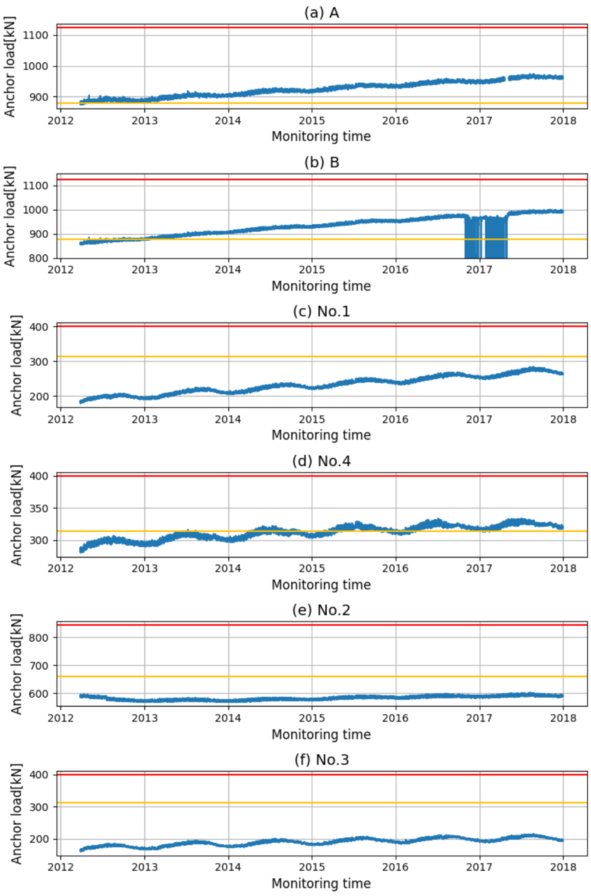

Figure 12. Tensile force of anchor (a)A (b)B (failure of measurement equipment around 2017) (c)No.1 (d)No.4 (e)No.2 (f) No.3.

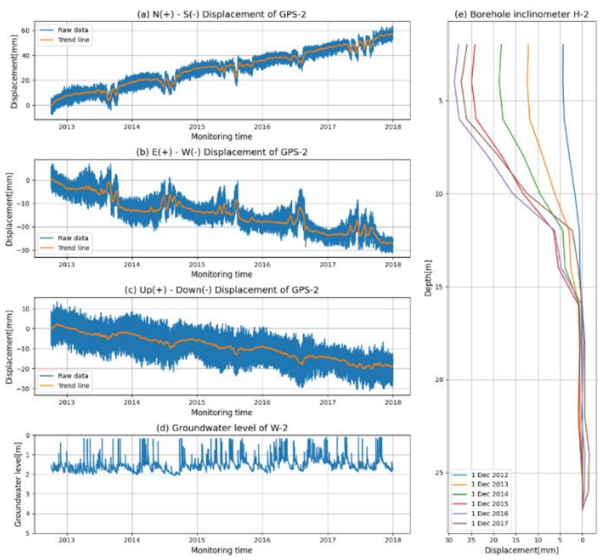

Figure 13. Monitoring results from 2012 to 2017 of (a)~(c)GPS-2, (d)W-2, (e) H-2

3.1.2. Overall slip

The upper portion of the connecting concrete beam of the lower steel pipe piles displayed noticeable movements towards the main road, as well as deformation of the waterway and road pavement caused by soil shoot-up and compaction. These signs were determined to be the culmination of the slip surface extending across the entire slope. Based on the extent of deformation observed and the presence of only one slip surface in the H-2 borehole inclinometer (Fig. 13(e)), it was inferred that the head and sides of the overall slip were shared with the upper slip.

Fig. 14 summarizes the observations of GPS-1 displacement near the center of the slope surface in (a) to (c), as well as the changes in the borehole inclinometer H-1 observations from 2012 to 2017 in (d). From (a) to (c), a gradual progression of displacement was observed from 2012 to 2017. The vertical displacement of GPS-1 shows that it initially rose until around 2015 and then began to sink around 2016 (Fig. 14(c)). This suggests that GPS-1 was located near the end of the upper slip and initially rose due to the predominant upper slip's pushing phenomenon, but then settled due to the development of the overall slip. From (d), it is evident that the upper soil mass continuously slid from around 19m below the surface.

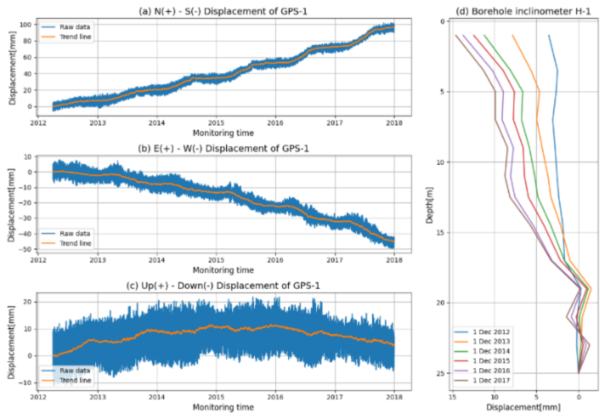

Figure 14. Monitoring results from 2012 to 2017 of (a)~(c)GPS-1, (d)H-1

3.2. Additional works in 2019 and 2020

Fig. 15 and Fig. 16 show longitudinal sections prepared for the two measuring lines. These maps were created by considering the observations from fieldwork conducted during construction, in addition to the observations described in section 3.1. Unfortunately, no post-service borehole investigations were conducted for the upper and overall slip, and only a few borehole inclinometers were available. Therefore, it is challenging to determine the precise depth of the slip surface for all the sliding blocks. However, due to the landslide being dominated by soft rocks like mudstone and the progressive failure that occurred primordially, the assumed slip surface was set based on the assumption that the ground displacement during construction has occurred since the beginning.

After analyzing the slip surface, soil pressures mobilized by existing countermeasures and the required performance to stabilize slips were calculated. While the current countermeasures met the performance standards in line 1, they fell short in line 2. On this basis, additional ground anchors and steel pipe piles were constructed in 2019 as countermeasures for the upper and overall slips, respectively, on line 2. Further, two new borehole inclinometers were installed in 2018 to monitor slips in greater detail and to deeper depths. In 2020, as part of the main road widening project, the slope at the bottom level was cut from a 1:2.8 slope to a 1:2.6 slope. Anchoring was simultaneously applied to the head of the lower steel pipe pile to prevent the lack of deterrent force at the bottom.

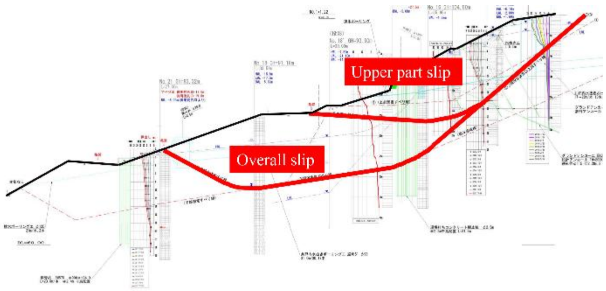

Figure 15. Cross-section view of the slips (Line 1)

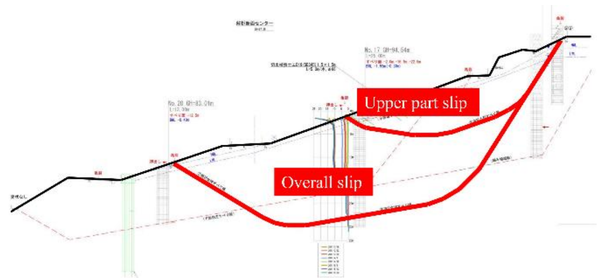

Figure 16. Cross-section view of the slips (Line 2)

3.3. Latest observation results

3.3.1. Upper slip

The data displayed in Fig. 17 reflects the readings obtained from GPS-2, water level gauge W-2, and borehole tiltmeter H-3 from 2012 to 2023.

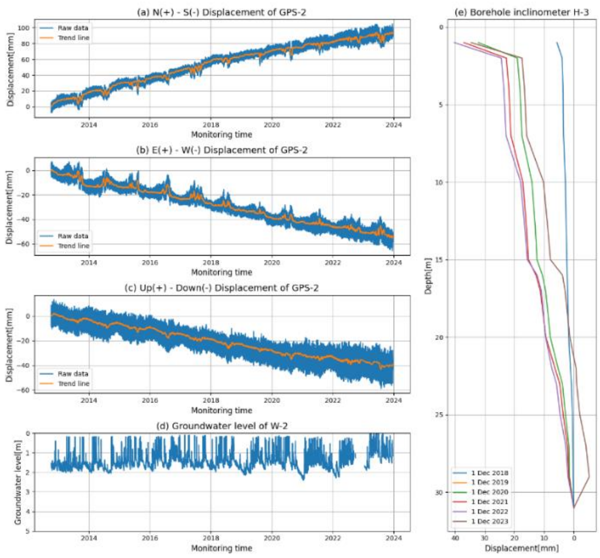

Figure 17. Monitoring results from 2012 to 2023 of (a)~(c)GPS-2, (d)W-2, (e)H-3

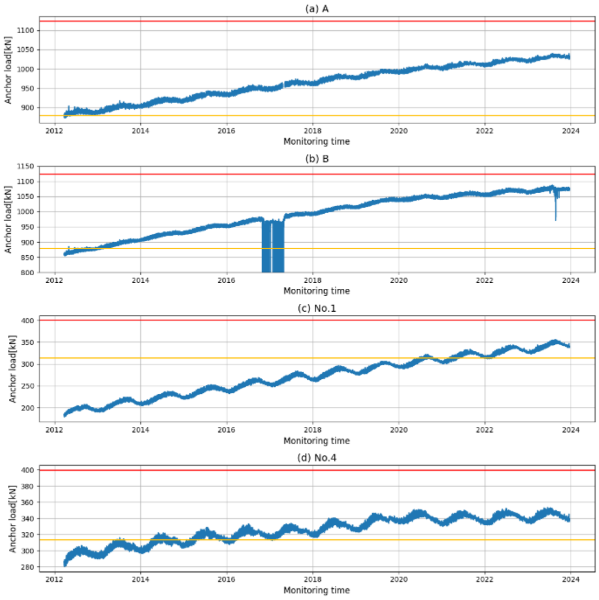

Figure 18. Tensile force of Anchor (a)A (b)B (failure of measurement equipment around 2017) (c)No.1 (d)No.4

The observations from (a) to (c) indicate that surface displacement persisted despite implementing countermeasures. Furthermore, (d) shows that the groundwater level remained high throughout the monitoring period. Notably, a significant displacement occurred near the surface in (e), likely caused by the movement of the upper slip end. Additionally, Fig. 18 demonstrates that there was no change from the upward trend of the anchor load.

3.3.2. Overall slip

Fig. 19(a)~(c) displays the GPS-1 displacement meter observations from 2012 to 2023, indicating the occurrence of displacement even after countermeasure construction. Fig. 17(e) further suggests the gradual sliding of the entire soil mass from a deeper position, indicating a slip surface deeper than the maximum depth of H-3. In contrast, borehole tiltmeter H-4's observation results (Fig. 19(d)) reveal the presence of a slip surface at a depth of 17 m from 2018 to 2021, followed by a sudden shift at a depth of 9 m and shallower from 2022. This corresponds to the lower slip described in section 3.3.3.

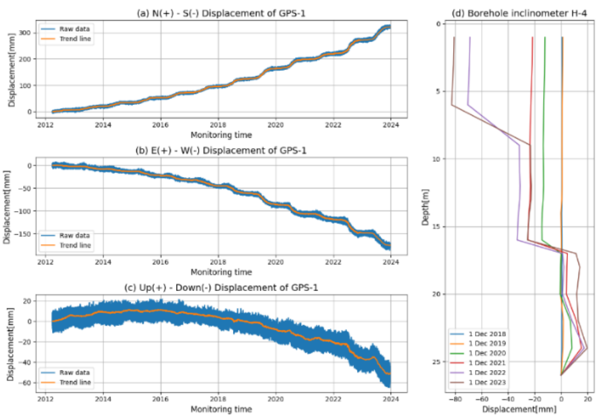

Figure 19. Monitoring results from 2012 to 2023 of (a)~(c)GPS-1, (d)H-4

3.3.3. Lower slip

The accelerated displacement of GPS-1 (Fig. 19(a)~(c)), the sudden observation of a slip surface at a depth of around 9 m in H-4 (Fig. 19(e)), cracks in the side road (Fig. 9) and pushing-out deformation in the slice cut (Fig. 10) suggested that a new lower slip had occurred as shown in Fig. 6.

On the other hand, no change was observed in the gauges of the lower steel pipe pile-head anchors installed at the same time as the cut (Fig. 20).

As detailed in section 3.2, although countermeasures were put in place, significant deformations persisted in both the upper and overall slip. Furthermore, surface slides were recently detected in the lower portion of the slope. Site A remains under constant observation as a location of critical management importance.

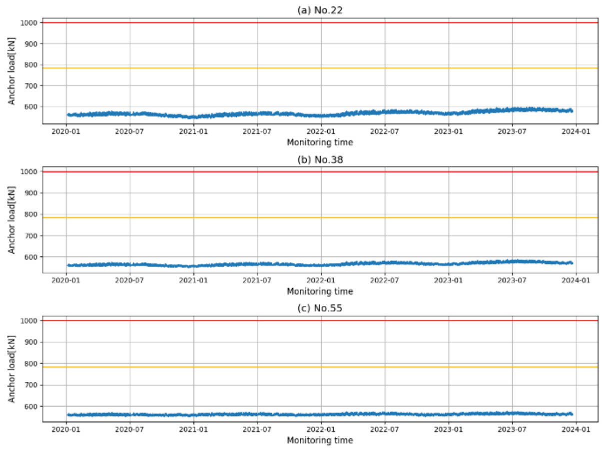

Figure 20. Tensile force of pile-head anchor (a)No.22 (b)BNo.38 (c)No.55

4. Conclusions

Monitoring records and ground behaviour on a large-scale cutting slope for over ten years were compiled and reported. Detailed field observations of the upper and overall slip were undertaken during construction and in-service to estimate the subsurface slip surface, and necessary countermeasures were successively considered. Despite efforts to suppress deformation, the upper and overall slip continued, and the lower slip became active again after additional construction work, therefore field observation needs to be conducted continuously. Since this site has a wide area, monitoring of interferometric SAR is also planned.

References

1) NEXCO Central Internal Report (2005~2023)