Utilization of Instrumentation Data for Averting a Potential Support Failure in a Deep Excavation Project

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Abstract

Deep excavations pose their inherent challenges to execute and the consequences of a support failure due to improper design, unforeseen ground behaviour, non-compliance of the construction to the design and specifications, etc. could be catastrophic. The risk of losing priceless human lives and incurring heavy costs against loss of equipment, project delay, litigation, etc. are extremely high for such challenging construction projects.

The paper is based on a deep excavation project undertaken by the authors' organization in a megacity in the Middle East in which the monitoring instrumentation showed unexpected data as the construction progressed. As a first reaction, its integrity was suspected, however, once data from multiple instruments installed in the same zone of the project were correlated the opinions changed. The data was then rightfully treated as a forewarning of a looming failure by the project stakeholders. Corrective actions were implemented in its wake and a catastrophic failure was averted. The monitoring frequency was increased and additional instruments were installed and monitored to keep a closer watch on the effectiveness of the corrective measures undertaken. The instrumentation data also aided in a deeper root cause analysis of the alarming deformations of the support system deformation, at later stages. The paper also describes the instrumentation monitoring scheme followed and data observed to elaborate the case study.

Keywords: deep excavation, deformation monitoring, risk mitigation

1. Introduction

The deep excavation, the case study of which is being discussed in the paper, is related to an underground metro station box comprising concrete rectangular boxes. These boxes were formed using permanent cast-in-situ diaphragm walls of thicknesses varying from 1.0 m to 1.2 m. The station was designed to cater to highway loading on either side of the median strip.

The construction methodology used was diaphragm wall, starting at the underside of roof level. The diaphragm walls were supported by a temporary propping system during the construction stages. The propping system consisted of a single line of temporary steelwork CHS props, along the length of the station just above the concourse level. The North side diaphragm wall was the designated headwall for the TBM breakthrough. On the East side of the station box, a sprawling residential community was also located.

In general, ground-level at the said underground station site was +9.5 m DMD. Sheet piles and diaphragm walls were installed to support the excavated ground. The first level of excavation was performed next to the sheet pile wall down to D-wall cut-off level i.e. +5.6 m DMD. Excavation depth inside the station box was -13.2 m DMD in common and -15.6 m DMD at the TBM cradle area which was in the middle width of the station extending to 34 m in length from the North headwall.

2. Instrumentation scheme

The monitoring instrumentation was deployed at the project as per Table 1 with the layout as per Figure 1. The excavation works started after the installation of the instruments external to the excavation and inside the D-walls and recording their base readings.

Instrument	Purpose	Quantity
Vertical inclinometer	Used to measure lateral movement due to construction activity manually	19 boreholes
In-place Inclinometer	Used to measure lateral movement continuously and automatically due to construction activity	5 boreholes
Vibrating wire piezometer	Used to assess the change in groundwater pressure	3 boreholes
Automatic ground water level recorder	Used to measure water level continuous during the construction period	2 boreholes
Groundwater standpipe	Used to assess the groundwater level manually	3 boreholes
Vibrating wire strain gauge	Used to assess load on the supporting struts	22 no.
Surface settlement point	Used to assess the surface settlement around the deep excavation	33 no.
3D prism target	Used to measure vertical and lateral movement in the D-walls	100 no.

Table 1: Details of the field instrumentation used for monitoring the underground station

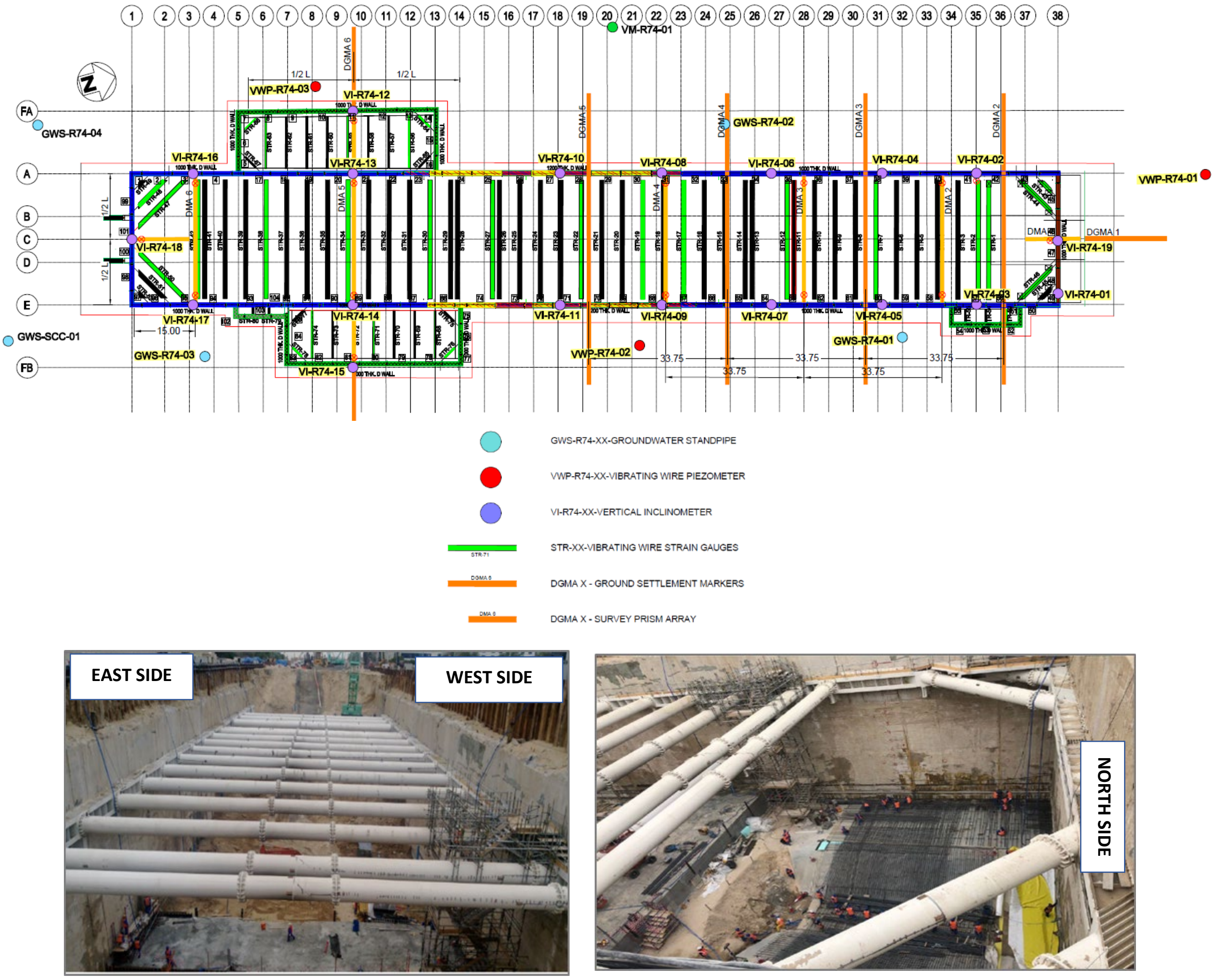

Figure 1: Instrumentation layout plan (above) and site pictures (below).

3. Diaphragm wall deflection incidences

In the three incidences given below, we will discuss the deflections observed in East, North and West diaphragm walls, correlating the data with ground water level recorder data and the strain gages data in that area.

3.1 Incidence-1 Deflection observed in East side diaphragm wall

The allowed limits of diaphragm wall deflections during construction were determined by the project's Consultants. Accordingly, amber, action, and alarm levels were defined for various instruments. These are marked in the monitoring data graphs presented below.

From the monitoring results, it was observed that the diaphragm wall was sensitive to any excavation below -11 m DMD. It reacted with a sudden increase in deflections when excavation was carried out below this depth. The movements were also observed with an increase in water level in that zone. Data from inclinometers, water level, prism targets, and strain gages were all correlated and confirmed the movement of the diaphragm wall. A close view of the location where the incidence took place is shown in

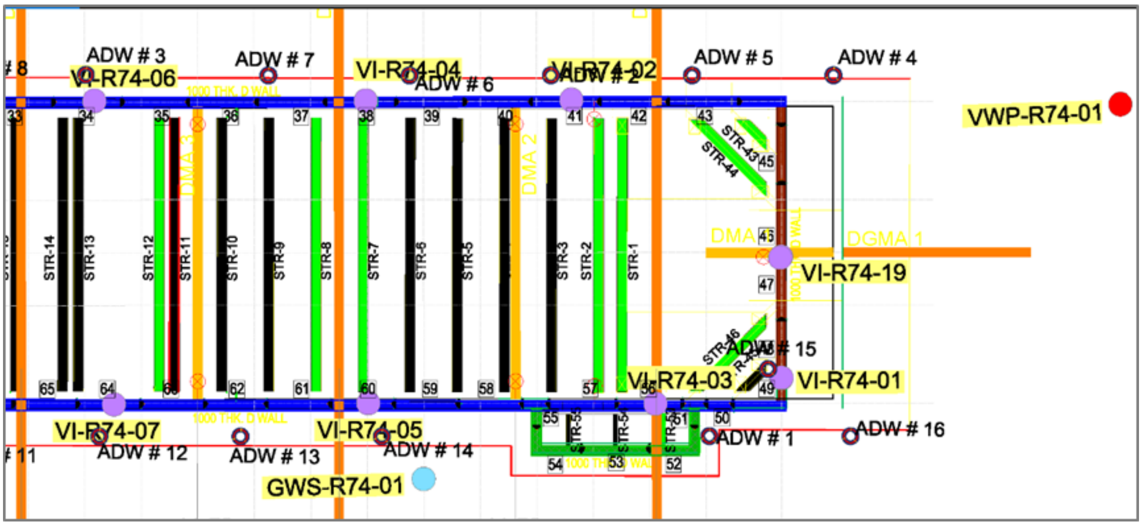

Figure 2, with all the instruments marked.

Figure 2: Close up view of instrument layout for East side diaphragm wall, showing inclinometers VI-03, VI-05 (incidence 1), VI-19 (incidence 2), VI-02 (incidence 3); dewatering well ADW # 01; water standpipe GSW-01 (automated later); Strut STR-1 with strain gages.

During the excavation period from April 19 to April 24, 2018, the recorded deflections in the inclinometer VI-03 showed sudden "jumps" up to 33 mm, as shown in Figure 3 below.

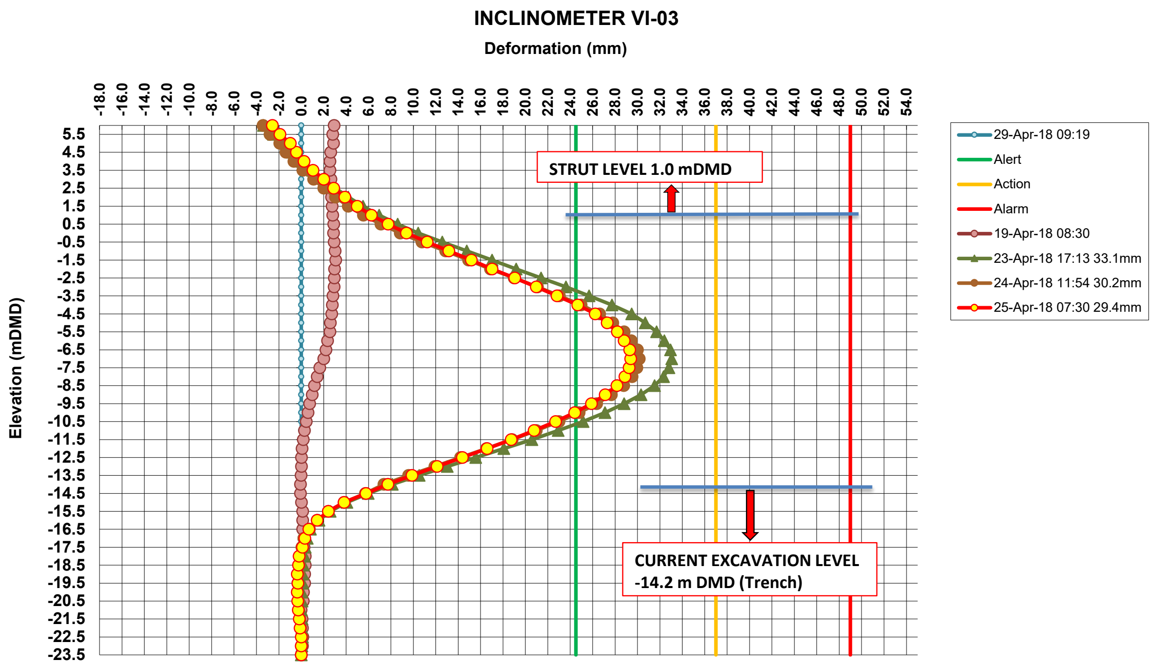

Figure 3: Inclinometer VI-03 data showing D-wall movement from April 19-24, 2018.

On May 1, 2018, the dewatering well ADW # 01 (location shown in Figure 2 above) was damaged by the nearby works and it was out of order for a few hours. During that time a rise in the ground water level of 2 m was recorded on the East side which caused the wall to deflect further. Inclinometers VI-03 and VI-05 recorded an increase of deflection of approximately 19 mm and 16 mm respectively as the water level reduced to the previous level after almost 24 hours. Refer to Figure 4 and Figure 5.

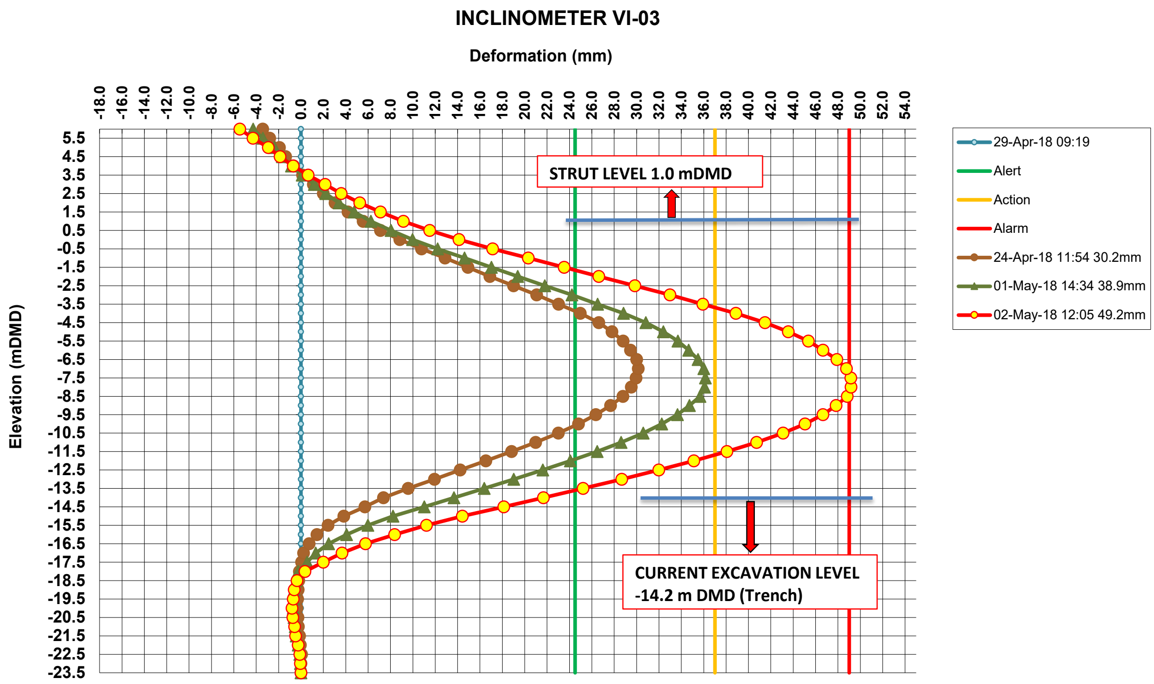

Figure 4: Inclinometer VI-03 data showing D-wall movement on May 1, 2018.

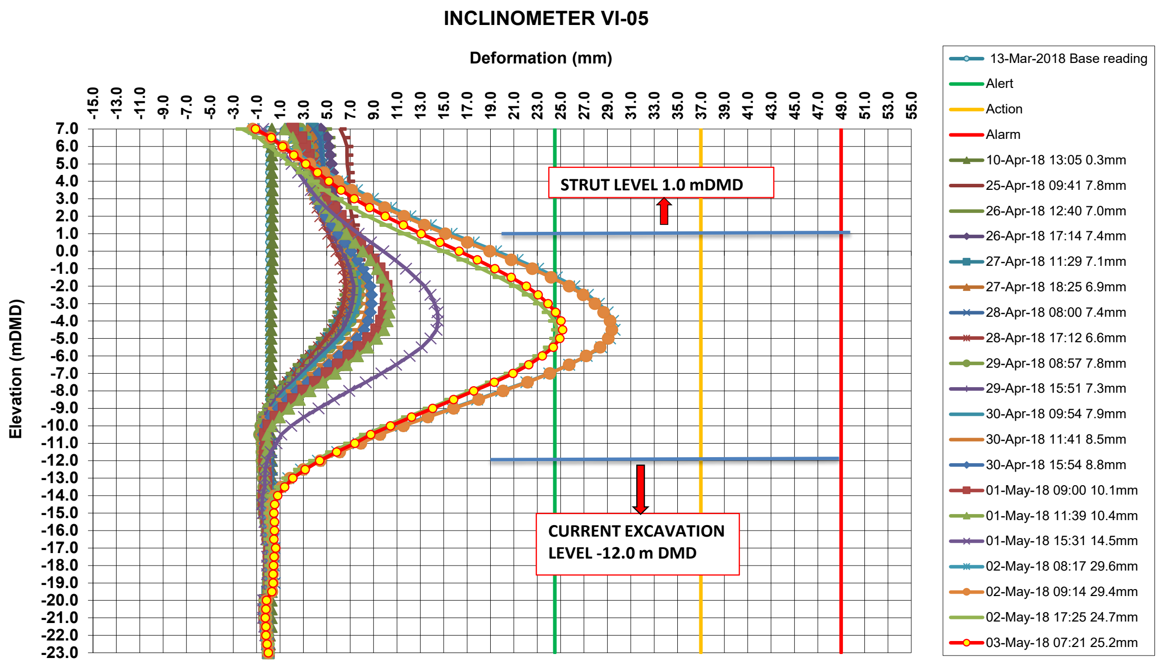

Figure 5: Inclinometer VI-05 data showing D-wall movement on May 1, 2018.

On May 8, 2018, morning, the dewatering well ADW# 14 on the East side got damaged and the repair lasted for approximately one hour. During this period the water level raised by almost 1.5 m as shown in water level data from the automatic water level recorder GWS-01 in Figure 8.

The inclinometer data of VI-03 showed a deflection of 4 mm and inclinometer VI-05 showed a deflection of almost 14 mm as can be seen in Figure 6 & Figure 7 respectively.

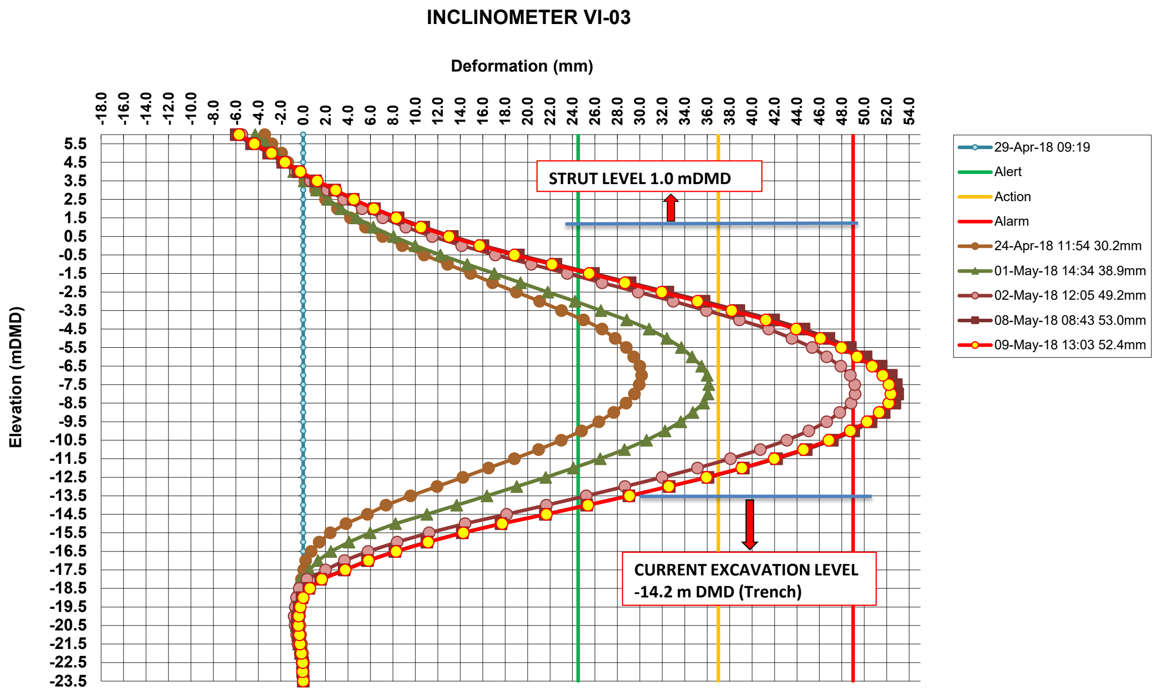

Figure 6: Inclinometer VI-03 data showing d-wall movement on May 8, 2018.

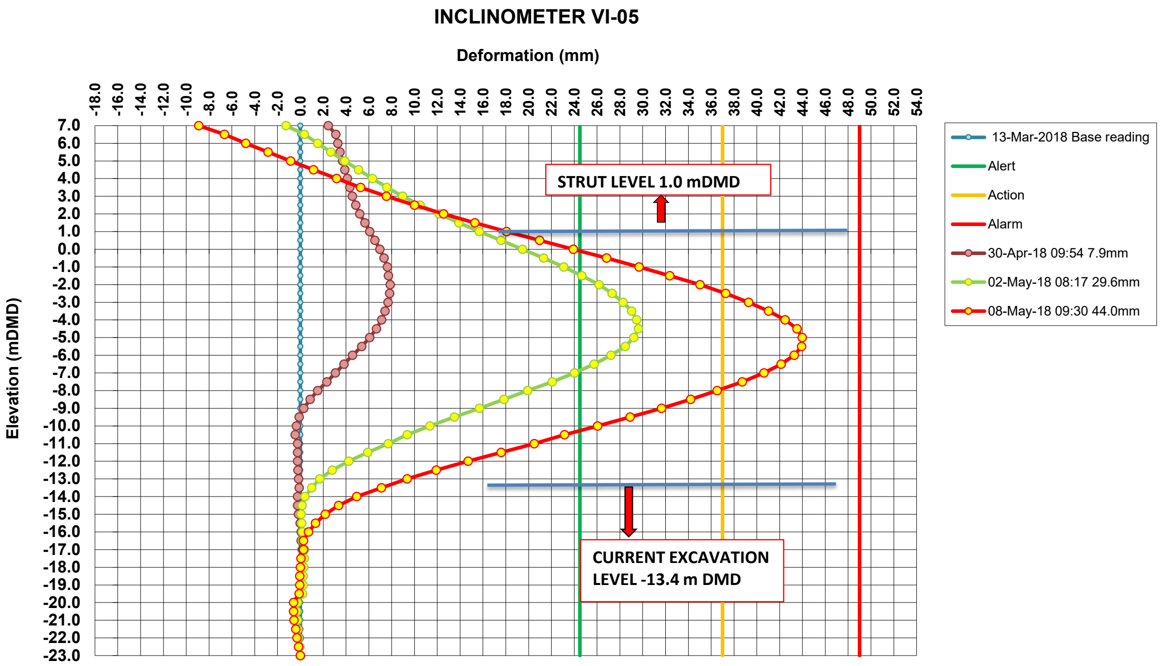

Figure 7: Inclinometer VI-05 data showing an increase in D-wall movement on May 8, 2018.

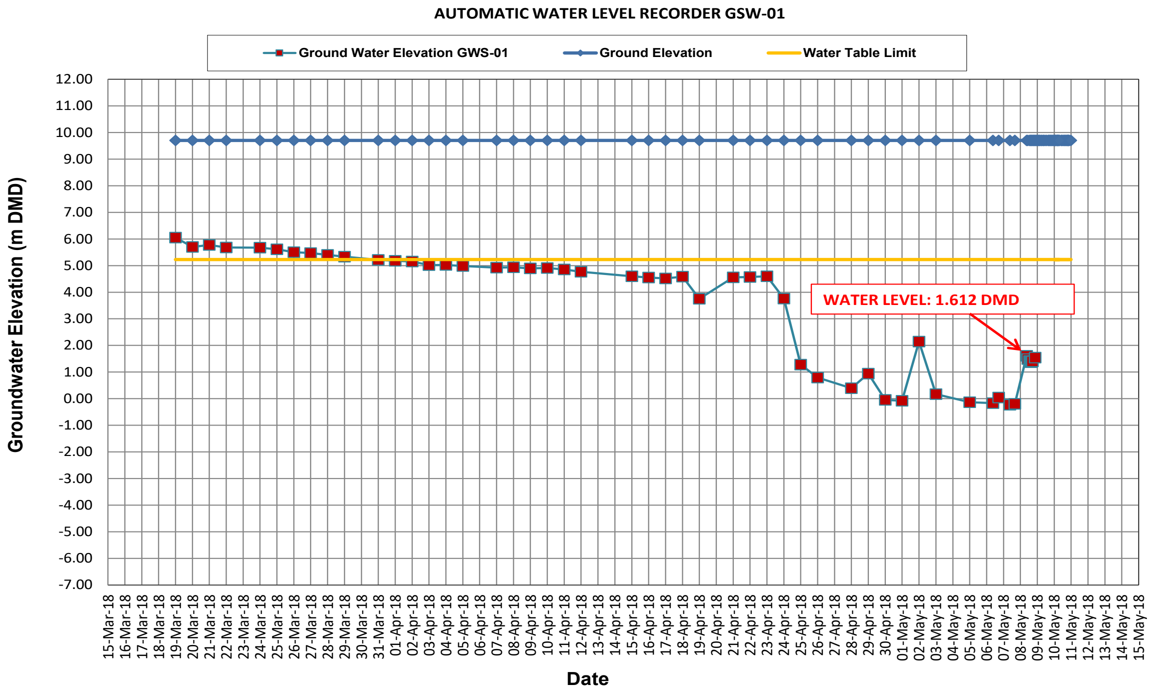

Figure 8: Water level data from automatic water level recorder GSW-01.

In Figure 9 below, a combined chart is plotted for data from inclinometer VI-03 and automatic water level recorder GWS-01. It shows that the diagram wall movement increases as the water level rises, although with a time lag. It also decreases as the water level decreases.

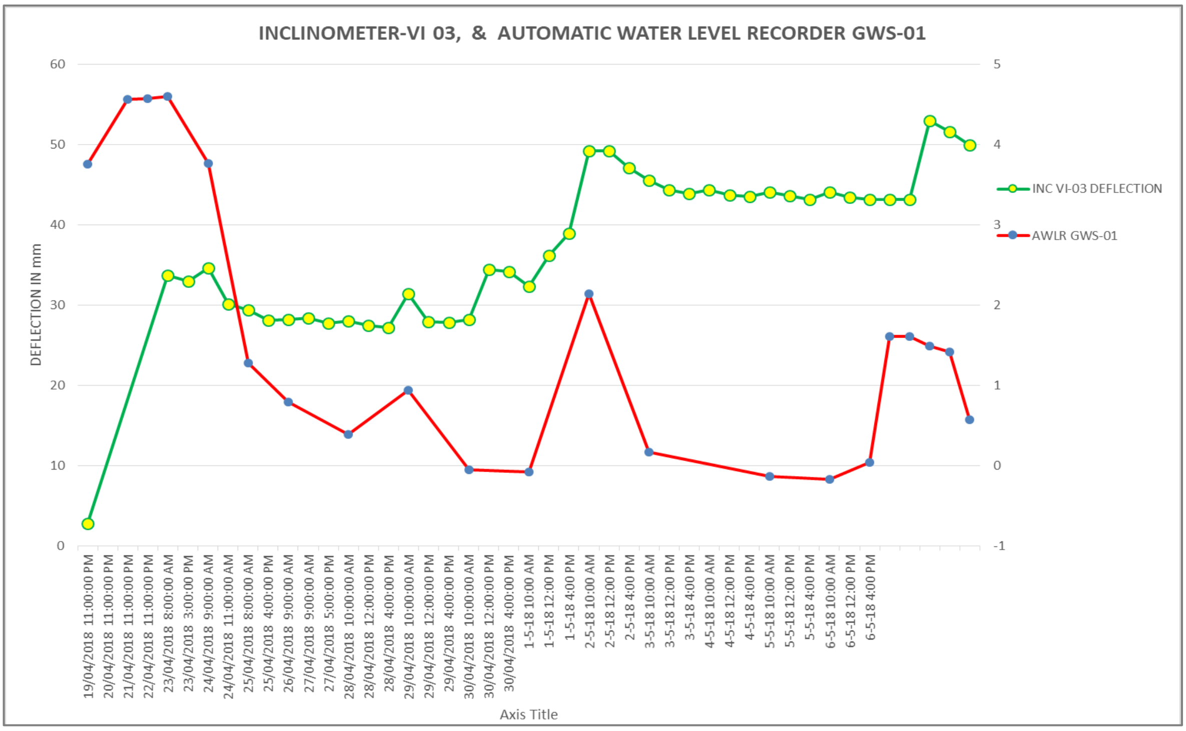

Figure 9: Combined chart for data from inclinometer VI-03 and water level data from automatic water level recorder GSW-01.

The data recorded from the prism targets, installed in close vicinity of VI-03 & VI-05, also showed the movement of the diaphragm wall on May 1, 2018, and May 8, 2018, as shown in Figure 10.

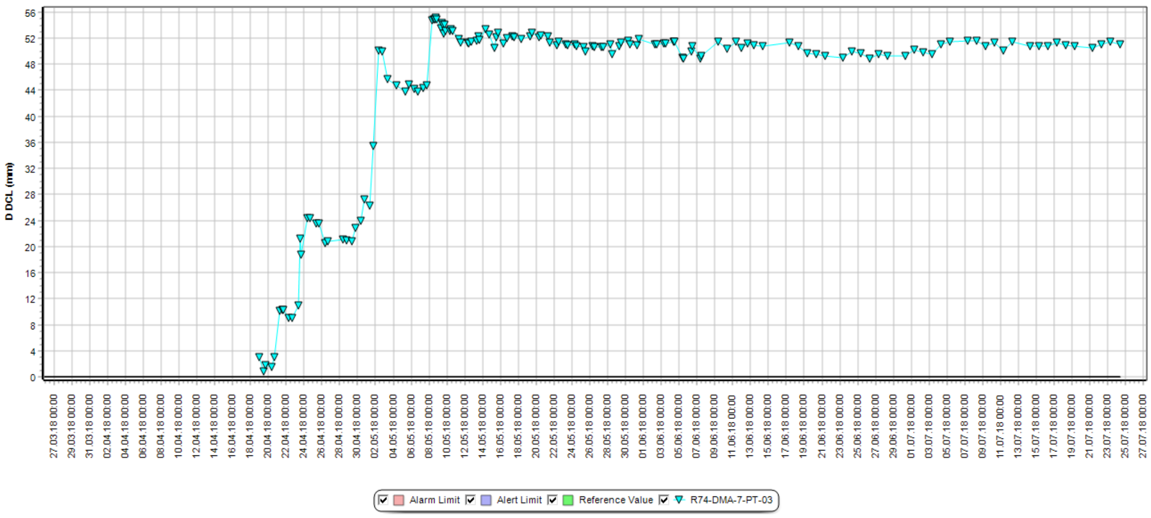

Figure 10: Prism target data showing movement on May 1, 2018, and May 8, 2018.

Strain gages installed on struct STR-1, supporting the East and West diaphragm walls, showed an increase in load on the same dates when inclinometer readings observed deflection with the rise in water levels. The strain gage data from strut STR-1 is shown below in Figure 11.

In the strain gage data, a high-velocity change in the strain values was also observed from 13th until 23rd April 2018. According to the daily site report, the mentioned velocity reflected the excavation activity.

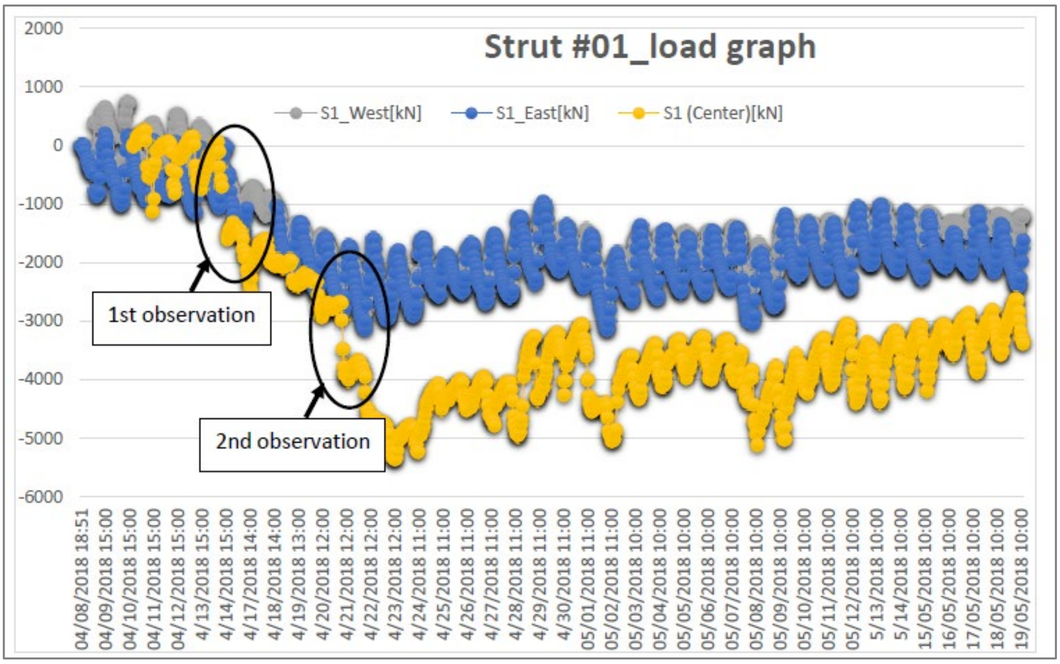

Figure 11: Data from strain gages installed on strut # 1, showing an increase in load.

3.2 Incidence-2 Deflection observed in North side diaphragm wall

April 19, 2018, onwards the inclinometer VI-19 installed at the North headwall, started to show a rapid deflection while the excavation was at -9 m DMD. Refer to Figure 2 for the location of inclinometer VI-19 and Figure 12 for the data showing the movement.

During the site inspection, it was found that the dewatering well was not constructed on this side of the diaphragm wall. After studying the inclinometer data, the civil contractor decided to construct and install the dewatering system behind the North wall on an urgent basis. The readings reached up to 25 mm before the dewatering system was functional. The readings got stable subsequently.

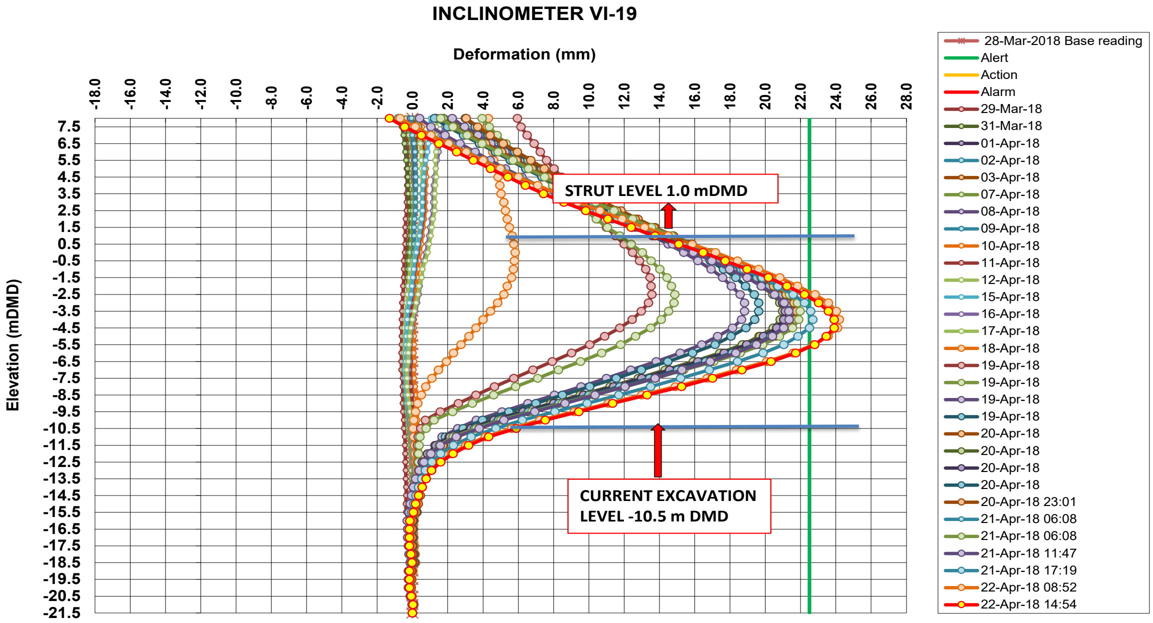

Figure 12: Inclinometer VI-19 data showing D-wall movement on April 19, 2018.

3.3 Incidence-3 Deflection observed in West side diaphragm wall

On April 22, 2018, during the excavation works on the West side of the station, a sudden increase in movements was observed in inclinometer VI-02 i.e. from 10.5 mm to 19 mm approximately due to the high water level on the West side of the station area. Refer to the data shown in Figure 13.

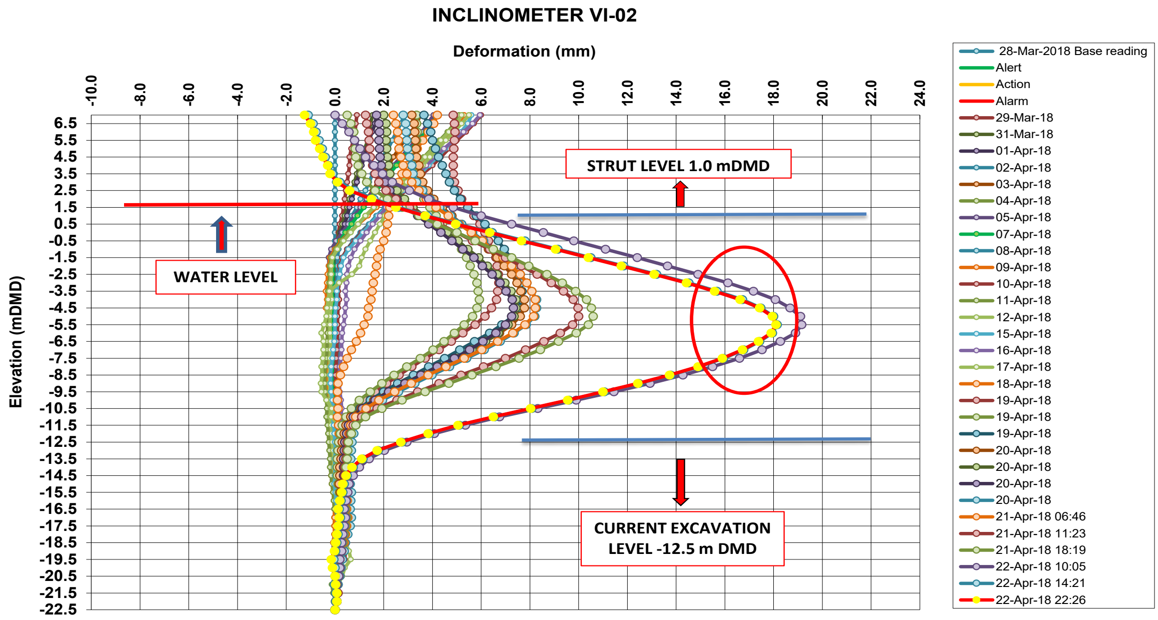

Figure 13: Inclinometer VI-02 data showing d-wall movement on April 22, 2018.

The next day, on April 23, 2018, up to 29.3 mm movement was recorded from inclinometer VI-02. Refer to inclinometer VI-02 data shown in Figure 14 below.

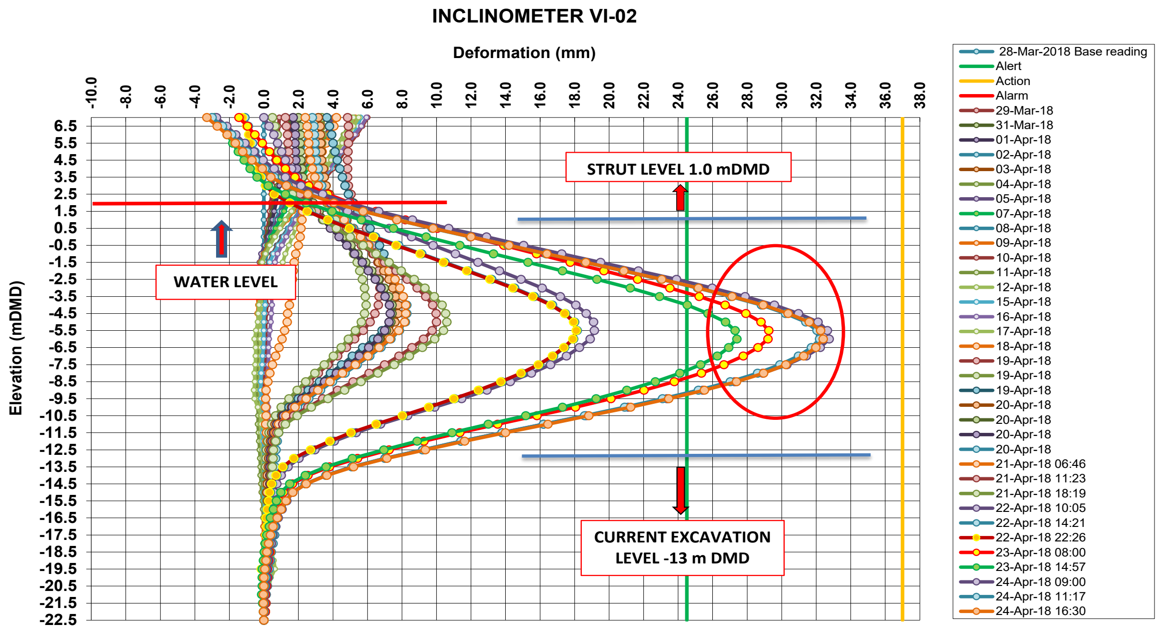

Figure 14: Inclinometer VI-02 data showing d-wall movement on April 28, 2018.

Looking at the readings of inclinometer VI-02 which observed a good amount of deflection in D-wall, the consultant and contractor concluded that this was occurring due to an increase in water pressure in the region. They thus decided to drill one dewatering well close to the inclinometer VI-02 location, to reduce the load (water pressure) at that location. Once the dewatering well became functional, the readings of inclinometer VI-02 stabilized.

4. Evaluation of the incidents

The consultant did an evaluation study to identify potential root causes behind the above-mentioned incidents. It involved a detailed investigation of the site activities around the time of incidents and a thorough examination of the monitoring data. Conclusively below activities were identified as the possible root causes for the incidents:

i) Partial failure of dewatering system in certain areas caused by rising of the water level behind diaphragm wall. Due to the high permeability of the soil, the water level rose quickly causing extra stress on the diaphragm wall.

ii) Commencing excavation at the headwall before constructing the slurry wall and dewatering within it.

i) Uneven excavation within the station box.

ii) The overall quality of the dewatering system and undertaking it in an uncontrolled and unconfined manner.

The consultant updated their models to reflect the above changes to create a new model that closely reflects the existing movement data.

5. Mitigation measures

To have better control over the situation and to avoid further movements of the diaphragm wall due to unaccounted for actions, the below strategies were devised and implemented on the site with immediate effect:

i) Resources were increased at the site to improve the evaluation of data and reduce the reaction time for taking any preventive action, in case required.

ii) Real-time monitoring: In place Inclinometers (IPI) were installed in VI-03, 05, 02, and 04 inclinometer wells to record readings automatically at higher frequencies. This covered the critical sections of the diaphragm wall on the East and West sides of the station box.

iii) An automatic water level recorder was installed in GWS-01 and GWS-1C groundwater standpipes to monitor the water level at higher frequencies.

iv) An automatic total station (ATS) was also installed to record readings of 3D prism targets at higher frequencies.

v) The dewatering system's design was re-evaluated and the required changes were made in it to make it effective.

vi) Additional dewatering wells were drilled nearby critical diaphragm wall sections to release additional hydrostatic stresses behind the diaphragm wall at remedial stages. It also increased the safety factor in the scenario of any unforeseen dewatering pump breakdowns.

vii) Flow sensors were installed at the outlets of the pump to give an early warning once the performance of the pump starts to reduce.

viii) Excavations were undertaken in a controlled manner, evenly on both sides from the center and working towards the sides and in layers no more than 1 m thick. The D-wall movements were checked during and after the removal of each layer.

6. Conclusions

The above incidence highlights the importance of data observed from geotechnical instruments, especially for sub-surface monitoring. The instruments played a vital role in providing factual data about what was occurring below the ground level. Data from different types of sensors helped in co-relating various parameters and achieving a high confidence level in the data, resulting in firm conclusions. This helped the stakeholders plan suitable remedial actions and implement them well in time. It resulted in preventing the possible failure of the diaphragm wall, managing the construction in a safe and controlled manner, and saving a great deal of time and money.

Acknowledgments

The contribution of our international office under which the project was executed is acknowledged. So are the inputs of the Technical Services Division at the Head office of our organization in India under which the initial draft of this paper was prepared.

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