DEFORMATION MEASUREMENT THE ATLAS CAVERN AT CERN

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Abstract

Caverns for large physics detectors as the one for the Large Hadron Collider experiments sit nearly 100 m underground and measure several tens of meters in length, width and height. The deformation of the cavern base slab over decades has a direct influence on the relative alignment of detectors to the accelerator. The expected long-term movements are larger than the fine adjustment of detectors and accelerators. In this paper, the measured deformations of the ATLAS experiment main cavern floor and lateral walls over nearly 20 years have been analysed. The measurement series have been performed in various time intervals getting down to half a year. The measurement techniques such as polar method (total station and laser tracker) and precise levelling allow to obtain sub-millimetre precision. The measured deformation reaches values up to 5.0 mm for the base slab and it is significantly (four times) lower compared to the predictions of the civil engineering consultants at the moment of the cavern construction. For the lateral walls, they reach up to 14.7 mm.

INTRODUCTION

Stability of underground facilities

The construction and maintenance of underground facilities remain one of the most challenging assignments in many industries such as mining, power engineering and transport [1]. The stability of caverns below ground level is affected by construction approach, excavation technique, geology, and in-situ stress [2]. The precise forecasting of the underground deformation is commonly discussed as part of the design, the planning, and the construction [3]. In most cases, monitoring is used to assure the stability of construction and thereby confirm the safety of a structure [4, 5].

Accelerators and experiments at CERN

The Large Hadron Collider (LHC) at CERN is the most powerful tool for Particle Physics research [6]. The LHC accelerator has been constructed based on the tunnel of the previous Large Electron-Positron Collider (LEP) [7]. The monitoring of the LEP experiments has shown vertical movements limited to a few millimetres with respect to the smoothed accelerator during the installation and operation. The observed initial sag after cavern construction and installation of the detector has been at the level of 2.5 mm for the experiments ALEPH and DELPHI. However, the stability of the civil engineering structure is a driving factor for the re-adjustment works on the LHC and its experiments.

The expected operation time of the LHC with more than 25 years is significantly longer than for the previous LEP accelerator, which implies a different consideration of deformations for upgrades of the accelerator and experiments. The plans for completely new facilities at CERN have been presented as well [8]. CERN’s future projects will probably be based on the existing technical infrastructure and knowledge. They should be constructed based on the experience gained from the civil engineering of the LHC project.

ATLAS (A Toroidal LHC ApparatuS) is a general-purpose detector to exploit the potential of the LHC accelerator [9]. It is placed inside the UX15 cavern and is the largest detector of the LHC with a length of 44 m and a diameter of 25 m. This huge detector sits in a cavern nearly 100 m underground and weighs 7000 t. The main part of the detector is supported by the 18 ATLAS feet that cover an area of 25 m x 9 m.

Civil engineering works and predictions

The civil engineering specification of UX15 did not include any limits for the movement of the cavern [10]. Extensive geological investigations were performed before LEP and ATLAS construction [11]. The experimental cavern for the ATLAS detector has impressive dimensions with a length of 53 m, a width of 30 m and a height of the cavern vault of 35 m. The cavern base slab has a thickness of 5 m and it is constructed using an invert to transfer advantageously the forces. The different walls and the vault of the cavern are 1-2 m thick. The total ATLAS underground complex includes besides the experimental cavern four shafts, various galleries and technical caverns. The largest technical cavern, called USA15, reaches 62 m in length and has a diameter of 20 m.

The civil engineering consultants have provided predictions for the vertical movements of the base slab of the completed ATLAS experimental cavern [12]:

1. Settlement of the cavern base slab by 2 mm prior to the detector installation
2. Settlement by an additional 5.5 mm consequent to the detector and infrastructure installation (8000 t)
3. Heave of the base slab 1 mm/year up to 12 mm due to pressure of the underlying ground close to the ATLAS feet area (central part of the cavern)
4. Stability (defined as movements lower than 1 mm per year) not achieved even after 15 years

The calculation that provides these values by the civil engineering consultants is considered conservative and could be interpreted as a worst-case scenario.

ATLAS cavern monitoring motivation

This paper treats the geodetic measurement of the ATLAS cavern deformations on the base slab and the lateral walls. The behaviour, of such a large underground construction, at a sub-millimetre level of accuracy and observed throughout 19 years, has never been studied. The main objective of this paper is to determine the magnitude and characteristics of the cavern deformation since its construction. In addition, the results of the base slab measurement are put in relation to the prediction of the civil engineering consultants.

METHODOLOGY

Reference and coordinate system

CERN has installed deep references close to the experimental caverns as extensometers in vertical boreholes executed from the main accelerator tunnel (see green dots in Fig. 1). These references should have the major advantage to be independent of the local tunnel movements as anchored in the bedrock 15-20 m below the tunnel level for point 1 [13]. The global movement of the area, tunnel and cavern, around LHC Point 1 cannot be evaluated but the deep references are sufficient to provide a common reference for the tunnel and the experiment with local long-term stability of the installation.

For the calculation of the measured coordinates and the analysis, two different coordinate systems have been used. The CERN Coordinate System (CCS) [14] has been used for the least squares adjustment in CERN's LGC2 software [15]. LGC2 takes into account the parameters of the CERN Geodetic Reference Frame (CGRF) [16] based on a densified geoid and an ellipsoid.

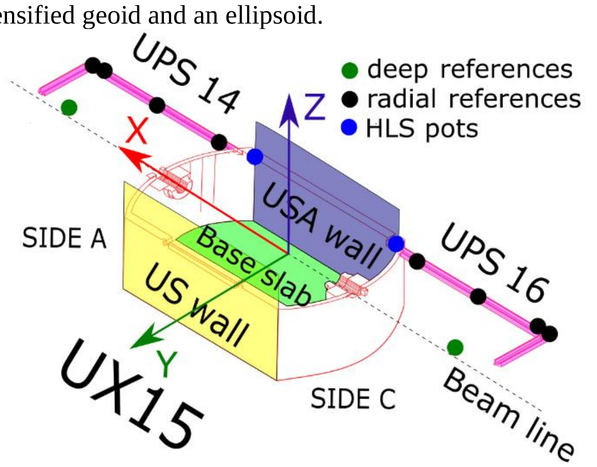

Figure 1: ATLAS survey coordinate system and reference

For the analysis of the results, the ATLAS survey coordinate system has been used that is nearly parallel to the cavern walls and the floor to ease the interpretation of the results (see Fig. 1). It is a modified local astronomical coordinate system with the nominal ATLAS Interaction Point as its origin and the X-axis along the nominal beam line projected in a horizontal plane [17].

Equipment and survey monuments

Direct optical levelling has been the preferred method for vertical stability until 2013. Precise distance meters have been used for the vertical height transfer from the cavern floor to the beam line level. For the planar and 3D measurements, manual total stations like the Wild TC2002 have been used up to 2013. Leica AT401/2 Laser Trackers have replaced advantageously the total stations and optical levels in 2013 [18].

For the base slab, core holes have been drilled to install reference points sealed in the floor and protected by a cover to avoid external damage to the survey reference. Plug-in or foldable brackets materialize the network points on the walls.

Metrology network and measurement epochs

During the progress of the detector construction and maintenance, the metrology network has been continuously adapted to serve the needs. In total around 100 reference points are part of the primary metrology network and are mainly installed on the cavern base slab (30x), on the lateral walls (55x) and in the technical galleries UPS14/16 (10x), (see Fig. 1). The main height references in the experimental cavern are two sensors of the Hydrostatic Levelling System (HLS) that are regularly linked to the deep references in the LHC tunnel. The reference in the horizontal plane consists of the furthest sensors of the Wire Positioning System (WPS) in the UPS14/16 galleries. They guarantee a high-quality geometrical link of the experiment to the accelerator on either side of the cavern [19]. Due to the position of the WPS sensors in relatively small galleries at around 60 m from the cavern centre, these points are less impacted by deformations

The available archived data contain measurements since August 2003. In Fig. 2, all epochs have been presented in time with division into measurements on the floor and on the walls. The raw measurements have been adjusted based on similar datum to assure the same conditions for all the epochs.

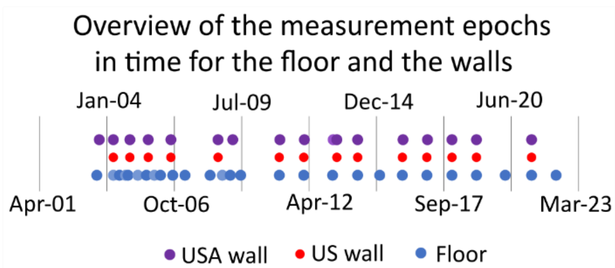

Figure 2: Overview of the measurement epochs in time for the floor and the walls

RESULTS AND DISCUSSION

Floor vertical stability

In Fig. 3, 4 and 5 the vertical deformation of the floor is illustrated. For the majority of the 26 epochs since construction, a heave has been detected. The exceptions are certain periods especially during the initial construction

(2003-2009) of the ATLAS experiment. The total deformation between July 2003 and March 2022 is adding up to a maximum of 5.0 mm. The average accuracy amounts to 0.09 mm at one sigma level for the point heights and it has been unchanged since August 2005. During the period between 2003 and 2005, the value is 0.18 mm. The first epoch in July 2003 is exceptional in terms of accuracy with a mean sigma of 0.35 mm, due to differences in measurement technique. The primary acquisition was based on polar trigonometry as distinct from precise levelling or laser tracker measurements in the later years. The largest deformations of the floor are measured for its central part. It is visible that relatively stable parts of the floor are close to the corners of the cavern.

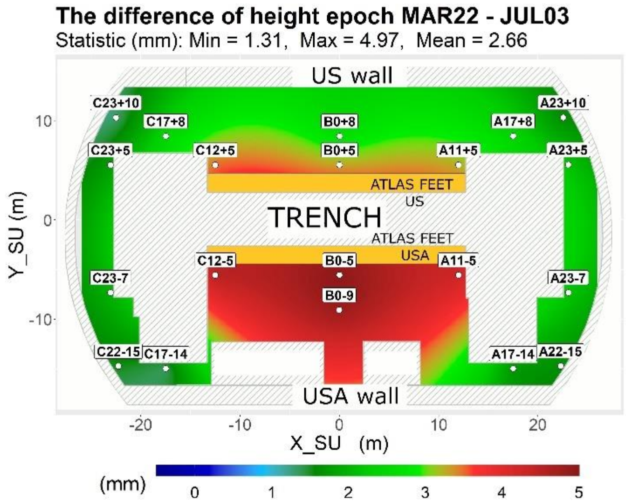

Figure 3: The vertical deformation of the ATLAS cavern floor Mar 2022 - Jul 2003

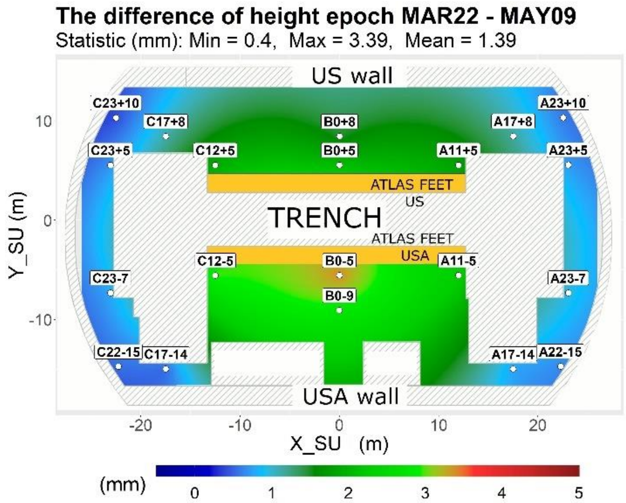

Figure 4: The vertical deformation of the ATLAS cavern floor Mar 2022 - May 2009

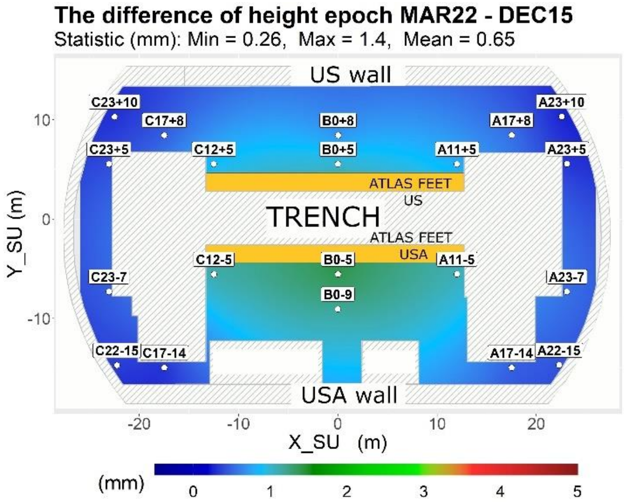

Figure 5: The vertical deformation of the ATLAS cavern floor Mar 2022 - Dec 2015

The periodically updated values of the floor deformation are critical for the ATLAS experiment. For that reason, the floor points have been measured more frequently than the reference points on the walls and geometrical levelling or polar trigonometry have been used. The measurement is focused on the base slab of the cavern and particular interest has been paid to the central part of the floor where the ATLAS feet stand, as a deformation of that area has a direct influence on the position of the experiment. Although the central area of the cavern (see Fig. 6) is crucial, it has not been available for direct measurements in several epochs as it has been obstructed by the ongoing ATLAS construction or upgrade works. In consequence, the network configuration and redundancy change from epoch to epoch.

The ATLAS detector axis is shifted laterally with respect to the cavern axis, which creates an unbalanced distribution of the detector weight on the cavern floor. In addition, the base slab includes several asymmetrically shaped trenches. These facts could cause differences of floor rigidity and explain the stronger heave of the cavern floor on the USA side next to the ATLAS feet area.

Centre and corners comparison on the base slab

Fig. 6 shows average vertical movement of the cavern centre and the cavern corners. Both centre and corners move up by around 1 mm during the first period after the handover of the cavern. The deformation got negative for the cavern centre between 2005 and 2008 when the ATLAS experiment construction entered the final phase. Since 2009 the LHC started the run period and the displacement speed stabilises at an average value of 0.15 mm/year with respect to the cavern corners.

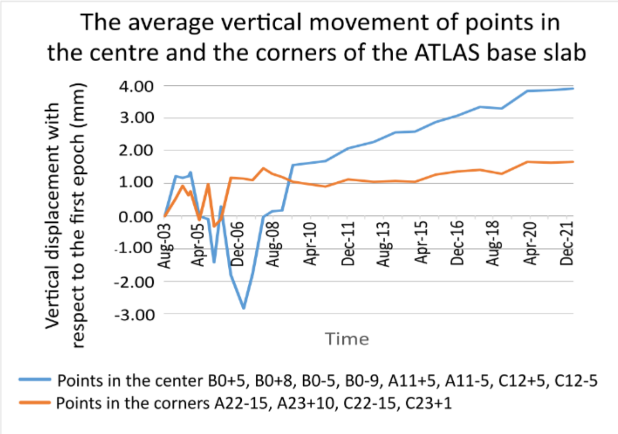

Figure 6: The average vertical movement of points in the central area and in the corners of the ATLAS base slab

Two opposite phenomena have an impact on the deformation in the central area of the base slab: the upward earth pressure and the load of the detector. They significantly influence the current position of the ATLAS experimental set-up. The used approach shows the relative deformation between the centre and the corners of the base slab. The corner areas are considered as the most stable zones on the floor, which has been confirmed by the long-term observation; see Fig. 3, 4 and 5. In contrast, the forces of the earth pressure and the detector load have the largest effect on the centre area.

The strong reaction of the concrete during the first year of monitoring provoked a rapid heave. The newly excavated cavern and the recently poured concrete could explain this displacement. It is possible to observe a significant reversal of the floor deformation trend during the construction phase of the experiment because at the same time, the major part of the 7000 tons load of the detector has been added on the base slab. Therefore, the floor has been pushed down exactly in the area of the ATLAS feet. After 2009, the measurement frequency has decreased to a yearly interval and took place during the maintenance period.

Generally, since 2009, the earth pressure has been deforming the floor inducing a heave in the centre. The magnitude of the movement is not as large as right after cavern construction but is noticeable and has a constant speed throughout the considered period.

Floor horizontal stability

In figures 7, 8 and 9, the horizontal displacement of points on the floor is shown. The arrows indicate the direction and magnitude of the displacement vectors. The accuracy of the points is presented as scaled error ellipses. Considering 14 measurement epochs and excluding the measurement of August 2003, the horizontal displacement does not exceed 1.3 mm for any point. The average horizontal movement of eight points near the ATLAS feet is limited to 0.5 mm in the period from 2004 to 2022. It is a confirmation that the centre of the floor remains stable throughout the entire monitoring period. The points on A-side and C-side tend to move towards the centre for most of the analysed epochs.

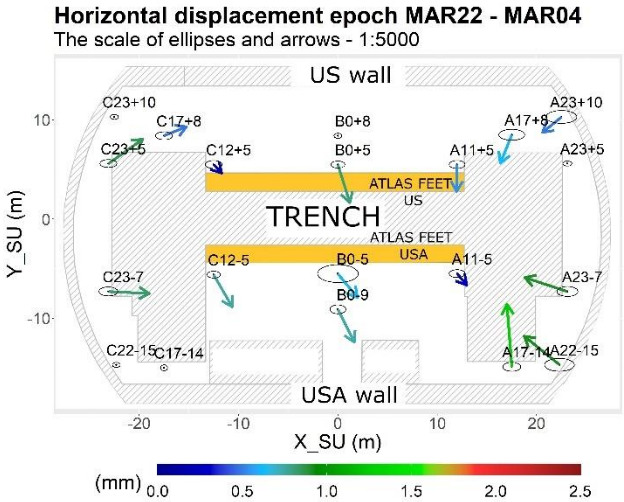

Figure 7: The horizontal deformation of the cavern floor Mar 2022 – Mar 2004

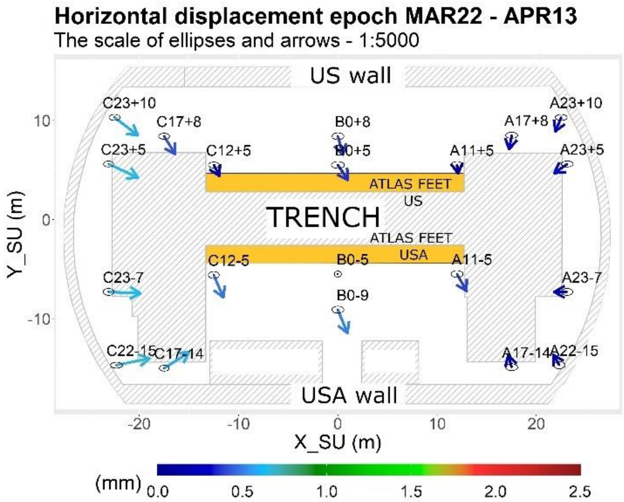

Figure 8: The horizontal deformation of the cavern floor Mar 2022 - Apr 2013

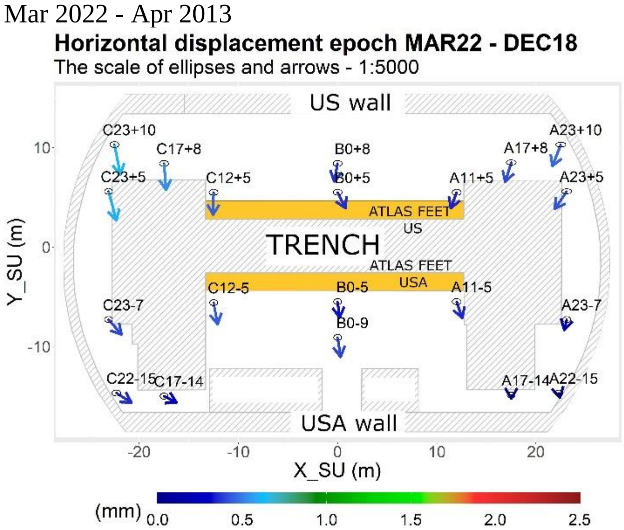

Figure 9: The horizontal deformation of the cavern floor Mar 2022 - Dec 2018

In the case of 2D floor deformation, the most important parameter is the deformation in the direction perpendicular to the experimental beam. It is crucial because any displacements could directly cause an eccentric position of the beam inside the detector. This may reduce the ATLAS detector performance and could contribute to the asymmetric ageing of certain detector parts [20]. The alignment in the longitudinal direction, beam direction, is less critical as a slight miss-alignment would keep symmetric distances of the detector components to the beamline.

Similarly, to the 1D stability, the most sensitive part of the floor is the central part, because of the direct neighbourhood of the ATLAS feet. The average horizontal movement since 2004 confirms a small shift of the central part of the base slab in the Y-direction. That behaviour allows to maintain the correct position of the experiment with respect to the nominal interaction point. On the other hand, we can observe a movement of points on A and C sides towards the centre of the cavern, which could be an effect of thermal expansion resulting in a scaling factor.

The first epoch acquired in August 2003 is not as precise as the following epochs. This can be explained by a different measurement technique and the environmental conditions associated with parallel civil engineering works such as temperature difference, significant airflow and construction co-activities. Further, the process of concrete setting influences the result. The epoch March 2004 as presented in figure 7 is the second measurement. The newly constructed cavern stabilized gradually after the end of the civil engineering works. In addition, the measurement methodology and the procedure have been still evolving at that time. The 2D movement decreases significantly after the ATLAS detector construction phase as visible in the figure 8.

In figure 9, a systematic movement of all points is visible. The displacement occurs towards the USA wall and it is difficult to interpret. It might be connected to the civil engineering works for HL-LHC in recent years. Due to this shift, the analysis for the remaining epochs shows horizontal movement along Y-axis. The influence of that displacement on the detector position is reduced as the differential heave of the cavern floor induces a rotation of the detector. At the beam line level this results in a shift to the US wall, which compensates the horizontal movement at floor level.

Walls stability

The walls USA and US have been subject to a similar analysis as the floor since 2003. The Y-coordinate differences have been calculated with respect to the most recent epoch in March 2021. However, the magnitude of the movement in the perpendicular direction to a wall is much higher for the walls than for the floor and reaches up to 11.2 mm for the US wall and up to 14.7 mm for the USA wall, the direction of the vectors is similar and indicates the centre of the cavern. In addition, the centre of the wall is more affected by the movement than points close to the corners, as it has been visible on the floor as well. The displacement has been increasing over years and it complies with the direction of the earth pressure.

Despite many similarities, the differences between the walls and the floor measurements are significant. The points on the wall are less numerous and their distribution is limited to the areas accessible by the access platforms. For that reason, the results are less reliable than the previous ones. Furthermore, the distribution of points on the USA wall is different than on the US wall and less adapted for monitoring purposes as the reference points are not equally distributed on the wall surfaces.

CONCLUSION

The precise observation of the ATLAS cavern for nearly 20 years gives some precious information on the stability and behaviour of the underground cavern. To meet the constraints applied to the detector positioning, it is necessary to take into account the deformation of the cavern, since it has an influence on the detector position. The values of the deformation reach 5.0 mm for the floor and 14.7 mm for the walls and are significant for the ATLAS stability. In addition, the non-linear character of the deformation makes precise forecasting extremely difficult. Furthermore, the civil engineering works for the HL-LHC in the period 2018-2022 could influence the deformation.

The perpendicular component to the considered surfaces has been extensively discussed in this paper. Whether we speak about the floor or the lateral walls, the largest displacement of points has been observed in the centre area but slightly shifted to the USA wall for the base slab. The design of the cavern and the excavated volume are asymmetrical and affects the base slab deformation. The asymmetry of floor deformation could be caused by the shifted position of the detector axis with respect to the cavern axis and the distribution of the trenches on the base slab as visible in Fig 3. The sense of movement in time has been towards the geometrical centre of the cavern either for the floor or the walls. The only exception is the behaviour during the loading phase of the base slab with the ATLAS detector.

It is possible to distinguish three main periods of the floor movements. The first is the phase of the end of the cavern construction, which is characterised by the rise of the floor. The second stage began with the construction of the ATLAS detector in 2005 and it was lasting up to the end of the loading of the floor in 2008. During this period, the floor experiences a sag in the centre. Finally, in 2009, the last phase of the movement stabilisation started and the heave of the centre was around 0.15 mm/year with respect to the cavern corners.

The measured vertical deformation has been significantly lower than the predictions of civil engineering that can finally be considered as very conservative and has never been reached since the handover of the ATLAS cavern. The floor showed, in the sense of civil engineering, a stable behaviour with movements of less than 1 mm/year since construction. The highest average heave since beam start has been 0.30 mm/year for a single point and the average heave since beam start of a floor point is approximately 0.15 mm/year. Even after nearly 19 years the heave continues for the points on the base slab.

The horizontal stability of the floor has been monitored using polar techniques. It is possible to observe the stabilisation period after the end of the ATLAS construction. The detector position constraints are stricter for the radial displacement with respect to the beamline than longitudinal. The average displacement of points in the centre of the floor is 0.5 mm, which makes it negligible compared to the vertical deformation.

The conclusion drawn from the characteristic of the base slab movement presented in the paper indicates the range and sensitivity of a measurement system that is chosen to allow the geometrical follow up of the detector construction and maintenance. Moreover, the detected deformation should be considered during the design of a reliable mechanical adjustment system.

The wall monitoring shows a significant deformation of both lateral walls. The deformation is three times larger than for the base slab. The weight of the detector, as well as the thickness of the base slab, might have direct influence on that. Especially, the US side wall is affected by the movement reaching almost 15 mm. It is a 4 mm larger value than for the USA side wall, probably as the USA side of the main cavern is surrounded by a larger volume of additional service caverns than the US-side wall.

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