Measurement and Temporal Analysis of Performance and Movements of Building Foundations

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Key words: Vertical Local Geodetic Network, settling measurement, movements of the foundations of buildings, performance of building foundations

SUMMARY

Measurement of the movements and deformation of building foundation structures can currently be performed using geodetic measurement techniques using automatic level, total station, GNSS receivers, hydrostatic communicating vessel systems, geotechnical instrumentation using extensometers and inclinometers and techniques for InSAR remote sensing satellites. The measurement technique adopted depends on the amplitude of the physical quantities to be measured and monitored: displacement, velocity and acceleration of object points defined in the building structure. The effect of the loading state variation applied on the structure of the building, during the construction and post-construction phases, interferes with the stresses of the various layers of the soil on which the building was built, causing movements of the structural elements of the building's foundations. These movements, from certain limits of magnitude, may generate damage and structural pathologies. The total settlings, differential settlings, rotations, relative deflections, lateral displacement and inclination can be highlighted from the possible movements of the foundations of buildings. This paper will present the various settling measurements performed with the work of digital level supported by reference points of stagnant levels, defined and executed off-site benchmarks (level references) and on-site benchmarks (level references), the latter being used for height transport at the moment of the measurement of settling pins. Proper care in the execution of the various level reference points is of fundamental importance in order not to compromise the reliability and quality of the settling measurements. In this work reference points are set in pillars of a building built over 50 years ago performed on cast-in-place concrete structures of the Franki pile type located outside the site. Measurements are made through the settling pins fixed in the building pillars. For the temporal analysis and monitoring of the settlements, 41 pillars were selected from the total 87 pillars of the building for the materialization of the settling pins, to be periodically measured at predefined intervals according to the development of the construction and the results achieved. Through the measurement data performed, the calculations of angular distortions between the respective monitored pillars are verified. In the same way, the various graphs are constructed: Settling x time, Settling speeds x time, 2D and 3D settlements through interpolation curves. This way, it is possible to evaluate the structural behavior of the building, as well as to follow and evaluate the settlings until it is stabilized, verifying if the projected performance was reached.

RESUMO

A medição dos movimentos e deformação das estruturas de fundações de edifícios podem ser realizadas atualmente através de técnicas de medição geodésica com a utilização de nível automático, estação total, receptores GNSS, sistemas hidrostáticos de vasos comunicantes, instrumentação geotécnica com a utilização de extensômetros e inclinômetros e técnicas por satélites de sensoriamento remoto do tipo InSAR. A técnica de medição adotada depende da amplitude das grandezas físicas a serem medidas e monitoradas: deslocamento, velocidade e aceleração de pontos-objeto definidos na estrutura da edificação. O efeito da variação do estado de carregamento aplicado na estrutura da edificação, durante as fases de execução da obra e pós-construção, interfere no estado de tensões das diversas camadas do solo sobre a qual a edificação foi construída, ocasionando movimentos dos elementos estruturais das fundações das edificações. Estes movimentos, a partir de determinados limites de magnitude, poderão gerar danos e patologias estruturais. Dentre os possíveis movimentos das fundações de edificações podem-se destacar os recalques totais, recalques diferenciais, rotações, deflexões relativas, deslocamento lateral e inclinação. Neste trabalho serão apresentadas as diversas medições de recalques realizadas com o emprego de nível digital apoiadas em pontos de referências de nível estáveis, definidos e executados fora da obra e pontos de referências de nível imediatos a obra, estes últimos utilizados para o transporte altimétrico no momento da medição dos pinos de recalques. O devido cuidado na execução dos diversos pontos de referência de nível é de fundamental importância para não comprometer a confiabilidade e qualidade das medições de recalques. Neste trabalho os pontos de referência estão engastados em pilares de edifício construído a mais de 50 anos executado sobre blocos de concreto armado apoiados em estacas moldadas em loco do tipo estaca Franki localizado fora das imediações da obra. As medições são realizadas através dos pinos de recalques fixados nos pilares da edificação. Para a análise temporal e monitoramento dos recalques foram selecionados 41 pilares do total de 87 pilares da edificação para a materialização dos pinos de recalque, de forma a serem medidos periodicamente em intervalos pré-definidos de acordo com desenvolvimento da obra e dos resultados alcançados. Através dos dados das medições realizadas são executados os cálculos das distorções angulares entre os respectivos pilares monitorados e verificados o seu desempenho. Da mesma forma, são construídos os diversos gráficos: Recalques x tempo, Velocidades de recalques x tempo, Curvas de isorecalques em 2D e 3D. Permitindo assim, avaliar o comportamento estrutural da edificação, assim como acompanhar e avaliar os recalques até a sua estabilização, constatando se o desempenho previsto em projeto foi alcançado.

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1. INTRODUCTION

Measurement of the movements and deformation of building foundation structures can currently be performed using geodetic measurement techniques using automatic level, total station, GNSS receivers, hydrostatic communicating vessel systems, geotechnical instrumentation using extensometers and inclinometers and techniques for InSAR remote sensing satellites. The measurement technique adopted depends on the amplitude of the physical quantities to be measured and monitored: displacement, velocity and acceleration of object points defined in the building structure.

In the metropolitan region of Recife-PE, Brazil, there are several examples of works that present the most varied design solutions related to the study of the behavior of building foundations.

This work is being developed using the geodetic measurement technique with the use of a very high precision digital level and barcode sight reading. The same has been carried out since May 2015, totaling twenty-one measurement campaigns to date, covering an interval of 1545 days and is associated with a research project under development entitled “Control and Monitoring of Settlements - Building under Construction of the Integrated Laboratory for Technology in Oil, Gas and Biofuels – LITPEG/CTG/UFPE”, favoring studies and research in the area of Applied Geodesy and Geotechnics.

For economic reasons, in this work, the "static" Level References were embedded in pillars of building structure outside the domain of the work, with more than 50 years of post-construction and installed on Franki piles.

Proper care in the execution of the various level reference points is of fundamental importance in order not to compromise the reliability and quality of the settling measurements. Studies show the stability of two types of reference points: in the first, located in the vicinity of the construction with deep rods anchored in stable soil layers (SEIXAS et al., 2012) and in the second, reference points set in pillars of a building built over 50 years ago performed on cast-in-place concrete structures of the Franki pile type located outside the site, to the detriment of surface level references located on the sidewalk near the construction and/or located two meters deep in the vicinity of the construction. Measurements are made through the settling pins fixed in the building pillars (SEIXAS et al., 2019).

The measurements of settlements and the study of the behavior of the foundation are carried out through the pins fixed on the building pillars. Through the measurement data performed, the calculations of angular distortions between the respective monitored pillars are verified. In the same way, the various graphs are constructed: Settling x time, Settling speeds x time, 2D and 3D settlements through interpolation curves. This way, it is possible to evaluate the structural behavior of the building, as well as to follow and evaluate the settlings until it is stabilized, verifying if the projected performance was reached.

This work aims to present the methodological procedure for the height determination of the settlement pins measured from stable reference points materialized outside the domain of the work for the case under study, as well as the temporal analysis of the performance and movements of building foundations.
The shortage of a practical material (from real case studies) and theoretical reference to the methodology for the control and monitoring of buildings by means of optical measurement procedures, located in urbanized sites, encouraged the development of this work.

2. METHODOLOGICAL PROCEDURE FOR THE HEIGHT DETERMINATION OF SETTLEMENTS PINS AND PERFORMANCE AND MOVEMENT ANALYSIS

In this item are presented the necessary steps for the height determination of the settlement pins and the steps for the analysis of performance and movement of foundations.

2.1 Height determination of settlement pins

The height determination of the settlement pins is carried out in five stages described below:

Step 1: Vertical Local Geodetic Network

This stage includes the definition of the Vertical Local Geodetic Network, including the manufacture of spherical pins to be embedded in at least two stable pillars of a constructed building and close to the building being monitored; the manufacture of “pins of semi-spherical surfaces” of the points of immediate support to the work; the manufacture of the support screw for the sight and materialization of the settlement pins; the manufacture of the semi-spherical pins of the base of verification and adjustment of levels. Concluding with the implantation of the stable reference points and the implantation of the immediate support points to the building being monitored.

Step 2: Construction of the verification base and digital level adjustment

This step involves the implantation of the semi-spherical pins of the base for checking and adjusting levels. The importance of checking and adjusting the level for collimation error, usually detected using the Kukkamaeki method, is highlighted, and the importance of verifying the performance and quality of the level from ISO 17123-part 2 (ISO, 2001).
Performance analysis is recommended annually and the level check before each measurement and settlement control procedure. In this work for the flexibility of surveys and verification of the digital level for the realization of the measurement campaigns, a basis for verification and adjustment of the level was built close to the building under monitoring. Allowing the level to be checked before, during and after the measurement procedure, the latter when necessary.

Step 3: Implantation of the settlement pins

In this stage, the pillars to be monitored are chosen and then the “female” screw to be fixed on the respective pillars are manufactured. The location of the settlement pins on the pillars of the building is usually performed with a hose level. After the location, the female screws are implanted. The importance of verifying the final height of the external and internal floor of the building on which the measurements of the pillars to be monitored will be carried out and the importance of fixing the “female” screw with appropriate vertical spacing for the final floor of the building is emphasized. So as not to compromise measurements and settlement monitoring. It was necessary to manufacture a “male” screw to adapt the “female” screw and support the sight.

Step 4: Measurement of settlement

In this step, the verification and adjustment of the digital level is emphasized before each settlement measurement campaign. Then, the survey of the Vertical Local Geodetic Network is carried out to measure the settlement and the measurement of the settlement pins after the height transport of the stable reference points to the immediate reference points to the building. The measurements are made in two series of 4 observations and after the execution of each leveling circuit, the closing error is verified.

Step 5: Data processing and determination of heights of the references points of the Vertical Local Geodetic Network and determination of the heights of the settlement pins

This step consists of determining the heights of the reference points of the Vertical Local Geodetic Network and of the settlement pins using the geometric leveling method. Processing can be performed using specific software and/or excel spreadsheets. From the series of observations, measurement campaigns, carried out it is possible to evaluate the behavior of the Vertical Local Geodetic Network over time, in addition to determining the heights of the settlement pins.

2.2 Analysis of performance and movement of foundations

In Burland and Wroth (1975) apud Milititsky et al. (2015) the possible movements of building foundations are presented and illustrated, highlighting total settlements, differential settlements, rotations, relative rotations (angular distortions), relative deflections and inclination. Figure 1 by Burland and Wroth (1975) identifies the meaning of each type of movement.
According to I.S.E (1989) and according to Figure 1 (Burland and Wroth, 1975):

- Settlement is called s and implies that the displacement is downward motion.
- Differential settlement is called δs and is the settlement, for example, of C in relation to D.
- Rotation is called θ and is used to describe the variation in the slope of the line that joins two reference points of the foundation.
- Angular deformation is called α.

- Relative deflection is called Δ and represents the maximum displacement in relation to the line that joins two reference points away from L.
- Slope is called ω and describes the rigid body rotation of the superstructure as a whole or a well-defined part of it.
- Angular distortion is called β and corresponds to the rotation of the line that joins two reference points taken to define the plummet.

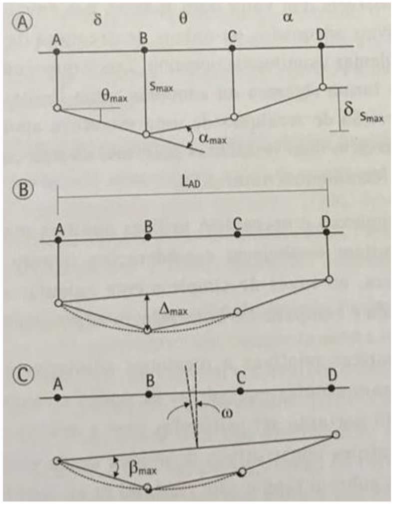

Figure 1: Definitions (Burland and Wroth, 1975): (A) definitions of settlement (s), differential settlement (δs), rotation (θ) and angular deformation (α); (B) definitions of relative deflection (Δ) and proportional deflection (Δ/L) e (C) definitions of slope (ω) and relative rotation (angular distortion) β

Limit values for angular distortion β can be observed in I.S.E. (1989) according to Skempton and MacDonald, Meyerhof, Polshin and Tokar and Bjerrum.
Burland et al. (1977) also highlight the following limit values of Skempton and MacDonald (1955):

- δ/l = 1/150 - structural damage to beams and columns of current buildings
- δ/l = 1/300 - cracks in building walls
- δ/l = 1/500 - safe building limit for which cracking is not allowed

According to Velloso and Lopes (2004), theoretically, a structure that suffered uniform settlement would not suffer damage, even for exaggerated values of the total settlement. The same states that in practice, however, the occurrence of uniform settlement does not happen, there are always differential settlements resulting from some type of load eccentricity, or soil heterogeneity and thus, the same author concludes that the limitation of total settlement is a way to limit differential settlement.
Burland et al. (1977) apud Velloso and Lopes (2004) suggest values of differential settlements and total limit settlements, applicable to the cases of usual structures, separating the cases of foundations supported by sand (δmax = 25 mm; s max = 40 mm for isolated shoes ; s max = 65

mm for raft foundation) and in clays (δmax = 40 mm; s max = 65 mm for insulated shoes; s max = 65 to 100 mm for raft foundation).
For the analysis of performance and movement of foundations in addition to the calculations of the movements illustrated in Figure 1, we add: the distinction between total settlement and partial settlement, the calculation of horizontal distances between the load centers of the building pillars, the calculation of total and partial speeds and respective accelerations. Graphical visualization based on these elements is essential to monitor the behavior of foundations, for example: graphics of settlement x time, curves of the same total and partial settlement, graphics of settlement speeds x time, among others (SEIXAS et al., 2009).
The procedures for the altimetric measurement are described below and the results are presented until the twenty-first settlement measurement (L21) of the case under study.

3. SETTLEMENT MEASUREMENT

The measurement of settlements is carried out during the period of execution of the work and after the construction of the work until the detection of stabilization of the settlements and as many times as necessary.

3.1 Study area

The study area is located in front of the Building of the Center for Technology and Geosciences (CTG) at Campus Recife of the Federal University of Pernambuco and involves the building of the Center for Technology and Geosciences, the central construction site of Av. Da Arquitetura, the building of the Integrated Laboratory in Oil, Gas and Biofuels and their surroundings.

3.2 Choice of pillars to be monitored

For the temporal analysis and monitoring of settlements, 41 pillars were selected from the total of 87 building pillars for the materialization of the settlement pins, in order to be measured periodically at pre-defined intervals according to the development of the work and the results achieved.

3.3 Geodetic infrastructure for measuring settlement

The geodetic infrastructure is composed of:
- 02 points of reference embedded in two pillars of the CTG school building (Figure 2)
- 04 pins of semi-spherical surfaces of the verification base and level adjustment
- 02 immediate reference points to the work (Figure 3)
- 41 settlements pins fixed to the building pillars

In the Technology and Geosciences Center (TGC) were implemented in 2015 two Level References set in two pillars of the ground floor of the external facade of the school building of the TGC. The pieces were made of stainless steel with spherical supports (Figure 2).

A B C

Figure 2: TGC Level References: A. TGC school building and front facade; B. and C. Materialization of the RN CTG01 with pin of spherical surface set in pillar of the school building of TGC. Data: 22/09/2015.

A B C D

Figure 3: Level References of the LITPEG construction. A. Construction of RN LITPEG01; B. Concrete of the base and fixation of metal rod; C. Fixation of BM; D. RN LITPEG01 and support of the invar leveling rod. Data:23/09/2015.

3.4 Instrumentation

The highly accurate geometric leveling for the transportation of altitudes was carried out using a Leica DNA-03 digital level (precision of ± 0,3mm / double leveled level) and a corresponding 2m invar ruler and respective logistical supports. For the quality of the observations, the level was programmed to carry out two series of 4 readings each, accepting the average of the observations in the series, whose amplitude was less than or equal to 0,06mm. Recalling that the “EC” command to correct the readings in relation to the effects of the terrestrial curvature was activated.

3.5 Procedure for the height transport of the reference points to the settlement pins

After defining the stable reference points, immediate reference points to the work and the definition of the settlement pins on the building pillars, the best route for the realization of the geometric leveling is evaluated.
Generally, the measurement of settlements includes the measurement of a Vertical Local Geodetic Network implanted in the vicinity of the work and/or close to the work. Leveling lines are measured between the reference points to allow control of the data collected. Thus, it is possible to level and counter-level stretches between reference points, level a closed loop in a ring or level the same line twice (Figure 4). For the leveling of the vertical network, the stations of the levels are chosen in order to keep the sighting method equal between the bachsight and foresight readings and thus eliminate the errors of atmospheric refraction and terrestrial curvature.

Figure 4 illustrates a sketch of the leveling lines measured (*l*1 to *l*12) during height transport from the stable reference points (RN CTG01 and RN CTG02) to the immediate reference points to the work (L1 and L2) passing through the reference (RNA and RNB) arranged on the basis of verification and level adjustments. The settlement pins P15 and P10 illustrated in a sketch in Figure 4, in this work, are used as change points during the measurement procedure between the immediate reference points L1 (RN LITPEG01) and L2 (RN LITPEG02), which allows also the measurement of the settlement pins located on this stretch of the work concomitantly with the measurement of the vertical network

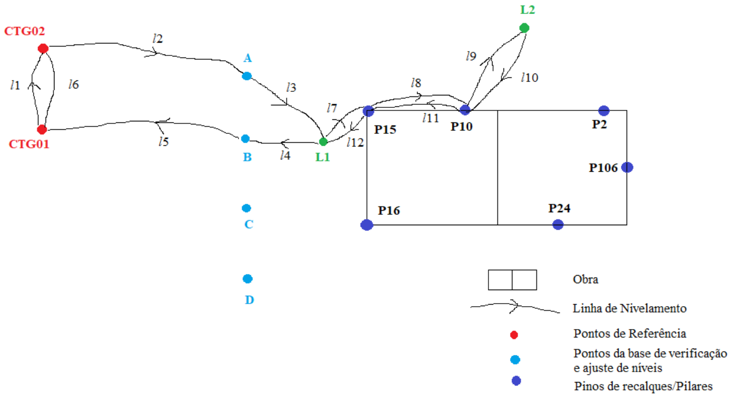

Figure 4: Illustration of leveling lines *l*1 to *l*12 and respective reference points and object points

Figure 5 illustrates the height transport procedure performed in the field between the CTG building and the building under monitoring.

A B C D

Figura 5: Height transport: A. RN CTG01 to RN CTG02; B. RN CTG02 to RNA; RNA to RN LITPEG01; D. RN LITPEG01 to RN B. Date: 17/12/2019.

After the height transport is performed, the closing errors of the leveling circuits performed are calculated in the field. Then, the measurement of the external and internal settlement pins is started. In this Work divided into settlement pins with external access to the building (external leveling circuit) and settlement pins with internal access to the building (internal leveling circuit).

The measurement of the settlement pins is made concurrently with the leveling procedure of the vertical network. These are measured from single and/or double sightings, the latter for leveling control. Figure 6 illustrates the leveling stations (E1 to E9) executed in the external leveling circuit performed for the measurement of the settlement pins accessible externally to the building under monitoring. The settlement pins P15, P10, P2, P106, P24 and P16 are used as change points during the measurement procedure of the settlement pins of the external leveling circuit around the building. Figure 6 shows part of the measured pins and a sketch of the stations occupied by the digital level and the respective external leveling circuit.

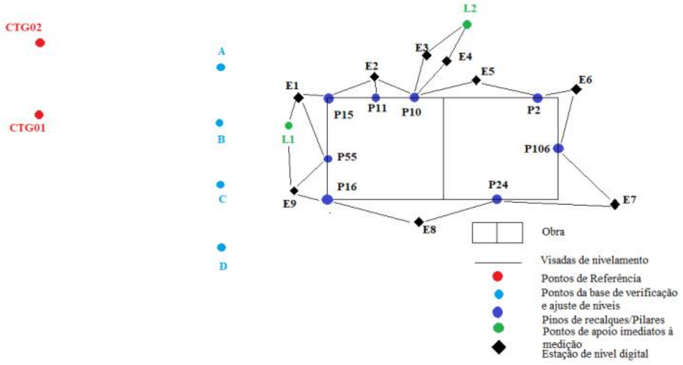

Figure 6: Leveling stations and leveling circuit external to the work

For leveling the settlement pins, it is important to pay attention to the amplitude of the intermediate sight, so that the effects of refraction and terrestrial curvature do not impair the observations made. In this sense, it was considered in this work a maximum amplitude of 25m between the level and levelling staff, when during the leveling procedure between the reference points the settlement pins are also measured. In Figure 6, for example, the illustrated settlement pins P55 (double measurement) and P11 (single measurement). For this maximum distance of 25m and for example a terrestrial radius of 6371km, an effect of terrestrial curvature of 0,05mm is obtained. Since the atmospheric refraction error acts in the opposite direction to the effect of the Earth's curvature, the effect of both will be less than this value for this range. This value of 0,05mm does not compromise the measurement results, in which case these corrections are not attributed in the observations made.
When measuring with the digital level, the effect of the terrestrial curvature is automatically computed in the observations made, as it has this function electronically embedded in the equipment. By informing the display values of the target readings corrected for these effects, making the measurement procedure more flexible.

4. TEMPORAL ANALYSIS OF PERFORMANCE AND MOVEMENTS OF FOUNDATIONS - MEASUREMENT L21

In this work, the visualization and monitoring of vertical movements based on the graphics of settlement x time, settlement speed x time and curves of the same settlement in 2D and 3D are presented as results. Thus, as the biggest angular distortion between the monitored pillars until the twenty-first measurement and settlement control (L21).

4.1 Visualization and monitoring of vertical movements

Table 1 describes the intervals between measurements in days, as well as the minimum and maximum settlements measured at each set of object points (settlement pins) in each measurement.

Table 3 - Intervals between measurements, minimum and maximum settlements.

Readings	**L01 0 days**	**L02 27 days**	**L03 63 days**	**L04 131 days**	**L05 161 days**	**L06 203 days**
Minimum settlement values [mm]	0	0,50	1,14	4,64	6,73	11,56
Maximum settlement values [mm]	0	4,08	10,18	17,74	21,69	26,17
Readings	**L07 237 days**	**L08 280 days**	**L09 337 days**	**L10 421 days**	**L11 497 days**	**L12 602 days**
Minimum settlement values [mm]	13,35	15,87	17,66	21,30	25,63	32,09
Maximum settlement values [mm]	28,57	31,15	35,30	43,26	51,21	60,61
Readings	**L13 678 days**	**L14 769 days**	**L15 862 days**	**L16 944 days**	**L17 1056 days**	**L18 1159 days**
Minimum settlement values [mm]	32,32	34,61	36,37	38,80	40,65	43,70
Maximum settlement values [mm]	63,19	66,40	71,17	74,97	78,91	83,44
Readings	**L19 1281 days**	**L20 1421 days**	**L21 1545 days**	**-----**	**-----**	**-----**
Minimum settlement values [mm]	47,17	48,23	49,92	-----	-----	-----
Maximum settlement values [mm]	90,02	92,85	96,03	-----	-----	-----

It appears that in the third Reading (L03) the maximum settlement reached a value close to 10mm; in the ninth Reading (L09), that is, practically in the first year of the work, the maximum settlement reached a value close to 35mm; at the fourteenth reading (L14), that is, practically after two years of work, the maximum settlement reached a value close to 66mm; in the seventeenth Reading (L17), that is, practically three years of work, the maximum settlement reached a value close to 79mm; and at the 20th reading (L20), that is, practically four years of work, the maximum settlement reached a value close to 96mm. It should be noted that a total of twenty-one campaigns for measuring and controlling settlement have been carried out to date, totaling 1545 days between the first campaign (L01) and the twenty-first campaign (L21). Between the first and the eighteenth campaign (L18), carried out, respectively on 24/09/2015 and 26/11/2018, the building was under construction and from the nineteenth campaign (L19), carried out on 28/03/2019, the building is built, completed, occupied and in operation (post-construction measurement).

The evolution of the object's vertical displacement is described over time through point velocity and point acceleration. Discrete observation times are interconnected to continuously describe the average speeds of the displacement mechanism (Figure 8).

Figure 9 shows the position of the monitored pillars with respect to the building and the respective curves of the same settlement with an equidistance of 1 mm corresponding to the total settlement of the settlement measurements carried out in this period of a little over four years.

Figure 7 shows how settlements took place over time.

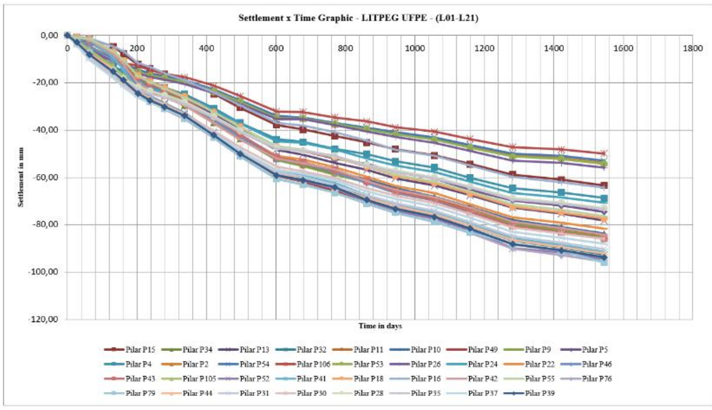

Figure 7: Accumulated settlement x time graphic

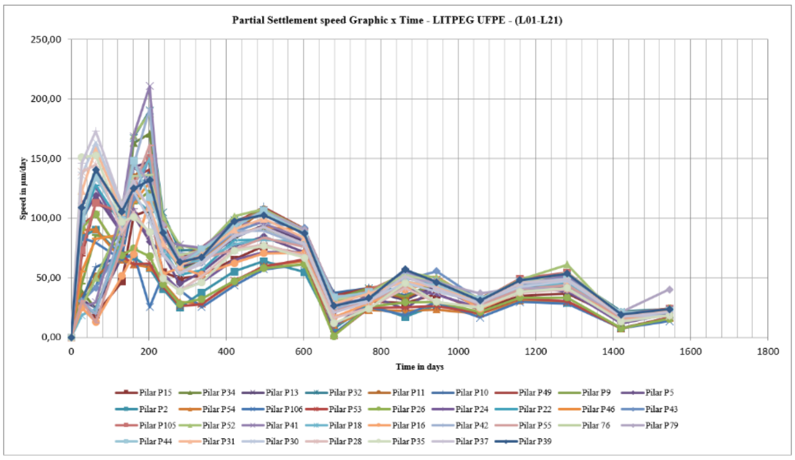

Figure 8: Cinematic motion interpretation of individual readings graphic.

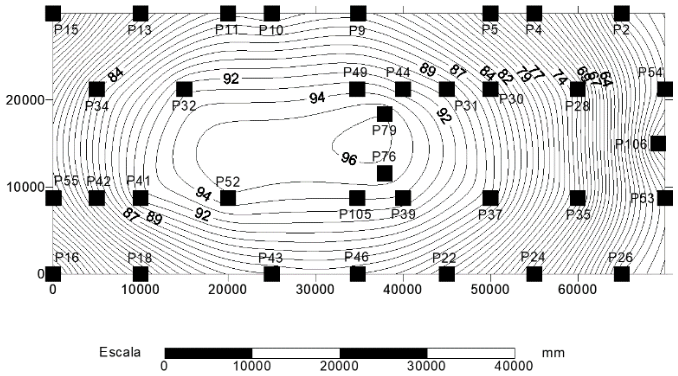

Figure 9: Curves of the same total settlement of 1 mm in 1 mm. Units in mm.

Figure 10 shows the representation of the curves of the same total settlement in a 3D view.

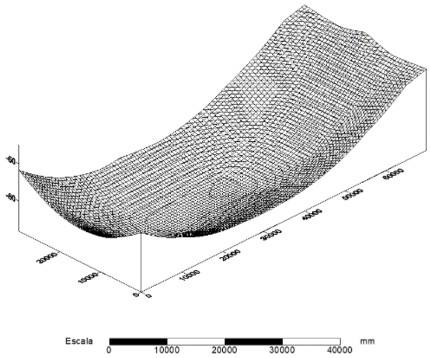

Figure 10: 3D model curves of the same total settlement. Units in mm.

4.2 Angular distortions between the respective monitored pillars

According to the settlement control, report L21 (Seixas e Seixas, 2019), the greatest angular distortion was 1/469 between the pillars P35 and P106.

5. CONCLUSIONS

According to the data collected, the evolution of the parameters described in item 2.2 is observed over time. Therefore, work should continue until it is concluded that stabilization has been achieved.

It is noteworthy that the quality of this work is directly related to the quantity of measurements performed, providing the maximum amount of data necessary for a better evaluation and analysis of the performance of the foundation and its superstructure.

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Medição 05 – 03/03/2016, Medição 06 – 14/04/2016, Medição 07 – 18/05/2016, Medição 08 – 30/06/2016, Medição 09 – 26/08/2016, Medição 10 – 18/11/2016, Medição 11 – 02/02/2017, Medição 12 – 18/05/2017, Medição 13 – 02/08/2017, Medição 14 – 01/11/2017, Medição 15 – 02/02/2018, Medição 16 – 25/04/2018, Medição 17 – 15/08/2018, Medição 18 – 26/11/2018 e Medição 19 – 28/03/2019), Recife - PE, 16/04/2019.
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