### AMP 317 settlement OF STRUCTURES (Version 2021)

### Programme Description

This programme guides NPPs to implement a settlement monitoring programme to manage the effects of ageing on safety-related and non-safety-related concrete structures in the scope, covered in AMPs 302, 304, 307, 310 and 318, caused by the degradation mechanism of settlement [1], [2]. The programme aims at maintaining the intended function of the concrete structures, as well as the systems and components structurally attached to them, during the life cycle of the plant, allowing it to obtain its LR for LTO purposes.

Settlement is mostly a plastic strain, which is therefore permanent, corresponding to a vertical displacement of the structure foundation owing to a variation in the effective stress state of the soil. It is called differential settlement when the foundation of the same structure undergoes different values of vertical displacement, generating structural distortion and cracks in concrete, mostly inclined, due to variations in the stress levels of the structure. Therefore, differential settlement is that addressed in this AMP, simply referred to as settlement hereinafter.

Settlement is considered positive when the vertical displacement is downwards and negative when it is upwards, also known as up-heave. The occurrence of settlement is inherent to the construction process of structures and its magnitude depends on the foundation type and geotechnical profile. It is predictable and is taken into account in the structural design basis of the plant [3], [4]. However, if the occurrence of the settlement continues beyond the predicted time, an investigation is carried out and the results are considered in the LR of the plant. In addition to the construction process, positive settlement can occur owing to dewatering and excavations carried out near the structure foundations, natural lowering of the groundwater level and, much more rarely, due to the presence of a collapsible soil layer in the geotechnical profile. Negative settlement can take place due to structure unloading, elevation of the groundwater level and, much more rarely, the presence of an expansive soil layer in the geotechnical profile. There are cases in which the structure undergoes positive and negative settlements with almost no plastic strain. It can occur owing to the variation of the groundwater level, and unloading and subsequent reloading of the structure corresponding to small stresses in comparison with the applied stresses due to permanent and accidental loads, and the association of both. An exemple of this behaviour is the case of the Angra 1 NPP in Brazil, presented in attribute 8.

Expansive and collapsible soils concern some types of clays whose physical-chemical properties, owing to the mineral composition, give them certain peculiarities that make their behaviour too complex. They consist of unsaturated clays that drastically change their behaviour in presence of water, i. e. with the increase of the water content. Expansive soils undergo volumetric expansion and collapsible soils undergo volumetric compression, generating a soil mass movement that, among other effects, can move the structure vertically, which means settlement [3]. Although this kind of soils cause settlement, the movement occurs regardless of the presence of a structure. Collapsible and expansive soils, the latter covered in AMP 310, are very unusual and dangerous for the stability of structures.

The foundations of safety-related and non-safety-related structures of NPPs are usually basemat or piles. The preferable supporting material over which safety-related structures are founded is sound bedrorock, especially the reactor and safeguard buildings. However, owing to the geotechnical profile of the site, the safety-related structure foundations of the same nuclear NPP, whether basemat or pile, may be founded on different materials, such as soil and bedrock. Sometimes it is necessary to adopt basemats and piles as foundations for the same NPP.

In the basemat cases where the supporting material is soil, the original soil is usually excavated and replaced by a highly featured dense pure sand backfill. In the piled foundation cases, the original soil may be maintained and depending on the geotechnical profile, especially the depth of the bedrock, the pile may either have its tip on soil or installed within the bedrock.

No matter the type of the foundation and the type of the supporting material, settlement always occurs, even in the case of sound bedrock. Sound bedrock may have small fractures that undergo accommodation when a heavy load is applied, causing settlement [5], [6].

Most of the settlement of a foundation, whether basemat or pile, over a sand layer is expected to end right after (from some days up to a month) the application of all permanent and accidental loads. However, for piles whose tips are supported by a sand layer, the settlement magnitude comprises the vertical displacement of the soil beneath the tip and the elastic displacement of the pile, which is negligible if compared to the former. In this case, the settlement has a much smaller order of magnitude than that of a basemat founded on the same layer and the predicted time to end is about the same [7]. Analogously to the previous case, the settlement magnitude of piles, whose tips are within the bedrock comprises the vertical displacement of the rock beneath the tip and the elastic displacement of the pile, which may not be negligible in this case when compared to the displacement of the tip. In this case, the settlement is expected to be within the same order of magnitude of basemats founded on sound bedrock and smaller than that of piles supported by a sand layer and the predicted time to end is about the same [7].

Concerning its behaviour, the supporting soil of the structures of a NPP are always be sandy (cohesionless), especially those safety-related. Clayey soils behave in a too complex way and, therefore, are avoided. If the geotechnical profile presents a layer of clay, especially soft clay, it is not recommended the use of basemat and any other shallow foundation, but a piled one whose depth exceed the clay layer. Depending on the thickness of the clay layer, negative skin friction on the pile is taken into account [7].

The layers which will support the foundations are subjected to tests to determine their strength, static and dynamic strain parameters and, in the case of sound bedrock, to confirm its soundness as well. If there is an enginnered backfill, it consist of a highly featured dense pure sand which cannot be marine and whose degree of density is be in accordance with the plant-specific design basis. The degree of density is achieved by a particle size curve well distributed leading to a low void ratio. The bedrock is subjected to a geotechnical investigation consisting of laboratory and in situ tests aiming at obtaining its strength, static and dynamic strain parameters. The same is done with the backfill immediately after its construction.

Concerning the need to carry out a settlement monitoring programme of the concrete structures of a NPP, if there have been no events that alter the behaviour of the soil and/or the sound bedrock, it is not necessary to carry out new geotechnical tests to determine the physical, strength, and static and dynamic strain parameters of the backfill. The parameters obtained from the geotechnical investigation carried out prior the beginning of the structure construction work can be adopted [8]. However, if an event such as an earthquake of magnitude exceeding the SSE of the plant may have altered the behaviour of the soil and/or the sound bedrock due to its energy or if the structures of the plant are undergoing severe vertical displacements, new geotechnical tests and new calculations of settlement is performed.

### Evaluation and Technical Basis

1. ***Scope of the ageing management programme based on understanding ageing:***

The scope of this AMP comprises the civil structure groups 1 to 9 [9], containment structures, and their component supports.. However, it is borne in mind that any structure besides these undergoes settlement.

The structure concrete elements that may be affected by settlement are:

1. Foundation;
2. Exterior concrete above and below grade walls;
3. Interior concrete walls;
4. Beams;
5. Columns;
6. Slabs.
7. ***Preventive actions to minimize and control ageing degradation:***

Structures undergo foundation settlements owing to variations in the effective stress state of the soil on which they are founded that can occur due to their construction process, excavation and/or dewatering carried out close to them, volumetric expansion of expansive soils, volumetric compression of collapsible soils and the occurrence of a high energy dynamic event, such as an earthquake. With the exception of the construction process of the structures, which is an inherent factor, and the excavation and/or dewatering in their vicinity, ,the other causes for the settlement to occur are natural and, therefore, cannot be avoided, but can be predicted and calculated. If the natural causes do occur and their consequences exceed the predicted settlement values, it can be associated with calculation errors due to inadequate assumptions, use of incorrect parameters due to poorly carried out geotechnical tests or incorrect interpretation of test results.

Therefore, the choice of a suitable site for the construction of a NPP, the performance of an adequate geotechnical investigation before the beginning of the work, the correct use of the parameters obtained from the geotechnical investigation, the correct interpretation of the geotechnical test results and the care of not carrying out excavation and/or dewatering close to the structures can be considered as preventive actions.

1. ***Detection of ageing effects:***

Settlement is a degradation mechanism whose ageing effect is the cracking of concrete structures. The main characteristic of the cracks caused by settlement is that they are mostly inclined. Their occurrence in concrete structures is usually the trigger that leads to a settlement investigation that begins with the implementation of a crack monitoring programme which consist of visual inspections that are repeated at a certain frequency using a standardized procedure and established by considering factors such as accessibility, physical condition, environmental exposure, and tolerance to anticipated degradation. If the crack monitoring programme confirms that settlement is taking place, a settlement monitoring programme is implemented to evaluate the behaviour of the concrete structures in the scope of this AMP.

As mentioned in the Programme Description section of this AMP, if the structure undergoes excessive and non-predicted strain or an earthquake of magnitude exceedingthe SSE of the plant takes place, it will be necessary to perform new geotechnical tests of the backfill to determine its current physical, strength, and static and dynamic strain parameters [3], [10], as well as of the bedrock. A summary of these tests and methods for calculation of settlements are presented below.

***Tests Carried Out on Sands:***

Sands are characterized by their compactness. So, in general, there are loose, medium, dense and very dense sands. As the sand grains are large, they present high coefficient of permeability, which means that they do not have a high hydraulic resistance to drainage. Therefore, settlements of sands take place rapidly, lasting from few days up to a month, which is considered instantaneous in comparison with the behaviour of clays [3].

Soils, including sands, present a rheological behaviour, i. e., they are stress × strain × time dependent which means that creep occurs. However, creep on sands can be disregarded most of the time.

Regarding a sand backfill, in the event of an earthquake of magnitude exceeding the SSE of the plant determined in the design basis, its best condition is that in which its degree of density corresponds to its critical void ratio. The critical void ratio is that at which the soil can undergo strain without volume change. If the void ratio of the sand backfill is lower than its critical void ratio, the sand backfill may undergo dilatance and if the void ratio of the sand backfill is higher than its critical void ratio, it may undergo liquefaction, obviously below the groundwater level. Both cases may affect the structures founded on the backfill and, in these cases, further physical parameters tests, such as density, unit weight, void ratio and particle size curve, are carried out. These tests are carried out if the crictical void ratio of the backfill is unknown and an earthquake of magnitude excedding or not the SSE of the plant takes place or even if the earthquake does not occur [11].

If any other event that may alter the behaviour of the soil and/or rock, as well as if the structures of the plant are undergoing severe vertical displacements, new laboratory and in situ tests to determine the strength, static and dynamic strain parameters is carried out [3], [10].

The performance of laboratory tests on sands implies the use of samples disturbed by the sampling. Even though in situ tests are more suitable for sands, laboratory triaxial tests may also be carried out on samples molded with several different relative densities aiming at determining the strength parameters of each one of them, creating a range of possible values that are interpreted by a specialist geotechnical engineer. Triaxial tests are better than direct shear tests because the latter impose the failure plane which is not the actual failure plane for the stress state acting on the soil sample [3].

The best in situ test to be carried out on sand is the Cone Penetration Test (CPT) from which, through existing correlations, the strength and static strain parameters can be obtained [8].

The resonant-column test is the dynamic laboratory test that can be performed to obtain the dynamic strain parameters of sands. However, the issue of sample moulding is the same as that of the triaxial test and, therefore, the same procedure is applied, creating a range of possible values that are interpreted by a specialist geotechnical engineer [10].

The dynamic in situ tests consist of geophysical tests, such as cross-hole and MASW (Multichannel Analysis of Surface Waves). The cross-hole provides the velocity variation profile of the compression waves and the shear waves with depth. The MASW method uses the recording of surface waves and, as a result after processing the data, provides the velocity profile of the shear wave with depth [10].

Concerning sands, if a static laboratory test is chosen, a dynamic laboratory test is performed rather than an in situ test. The same goes for in situ tests.

***Tests Carried Out on Clays:***

Clays are characterized by their consistency. So, in general, there are soft, medium and hard clays. As clay grains are too small, they present low coefficient of permeability which means they have a high hydraulic resistance to drainage. Clays, especially soft ones, undergo large settlements for a long period that may last decades [3]. Unlike sands, the rheological behaviour of clays are predominant which means that they are highly stress × strain × time dependent and creep is taken into account. Therefore, owing to their behaviour, clays are not expected to be an acceptable soil to support the structures of a NPP, especially those safety-related.

Just for the sake of clarity, suppose the fictitious cases concerning a clayey backfill supporting NPP structures, or an existing geotechnical profile comprising a layer of clay thick enough for the NPP structures to undergo major deformation. First of all, a geotechnical engineer with expertise in soft soils is required. Certainly, laboratory drained triaxial tests will be requested to provide drained strength parameters of the clay, in addition to several consolidation tests to determine the compressibility parameters to allow the evaluation of the total amount of settlement and its duration [3]. The sampling of clayey soils has to be carried out by qualified and experienced personnel in order to obtain undisturbed samples. The CPTu (Cone Penetration Test with Measure of Pore Pressure) in situ test which also provides, through existing correlations, the drained strength parameters of the clay, may be requested as well [8].

In the case of a clay layer loaded by structures built for almost 40 years, as is the condition of NPPs aiming at obtaining their LR for LTO purposes, to perform undrained laboratory tests, which provide undrained strength parameters, is meaningless.

Concerning the clay behaviour in the case of an earthquake occurrence, the effective stress state of the clay decreases due to the increase of the pore pressure leading to loss of strength and, consequently, to excessive distortional strains because of the shear stresses.

***Tests Carried Out on Rocks:***

Core samples are taken from the bedrock to be subjected to compression laboratory tests aiming at obtaining the rock strength parameters. Boreholes are drilled in the rock to perform geophysical tests to obtain dynamic strain parameters, as well as 360° videos to assess the degree of internal fracturing of the rock [5]. If tests on rocks are necessary, they are carried out and interpreted by a geotechnical engineer with expertise in Rock Mechanics.

***Settlements on Sands:***

The calculation of the settlement of a structure founded on a sand layer is performed using the Theory of Elasticity [12] which requires the static strain parameters obtained from the tests addressed in section 3.1. In order to perform a conservative calculation, pure sands are always be considered cohesionless.

As the settlement on sand takes place rapidly, lasting roughly a few days or a month at the longest, it is considered almost instantaneous. Based on this fact, if the geotechnical profile shows only a layer of sand overlying a sound bedrock, it is highly unlikely that structures founded on this layer are still under settlement around 40 years of lifespan, when a LR of NPP is requested for LTO purposes. However, if there is any evidence that the structure is moving vertically, a settlement monitoring programme is implemented.

***Settlements on Clays:***

The behaviour of saturated clays is highly stress × strain × time dependent. There are two mechanisms delaying the clay strain when subjected to stress states: hydraulic resistance to drainage of the water filling the clay pores (volumetric strains) and the viscosity of the adsorbed water (distortional and volumetric strains). The latter mechanism has recently been object of several researches in Rheology of Clays [13].

Terzaghi's theory, although a reference in consolidation studies, may lead to a non-conservative predicted settlement value [3]. For this reason, the calculation of settlement on clays are performed using an updated consolidation theory that takes into account the continuity of the compression process even after the pore pressure comes to negligible values and the delaying mechanism thereafter is solely the viscosity [13].

The static strain parameters are obtained from the tests addressed in section 3.2.

***Settlements owing to dynamic actions:***

In this case, the calculation of the settlement is performed by a 3D finite element soil-structure interaction software whose results provide the stresses generated in the soil-structure system owing to the imposed dynamic loading.

1. ***Monitoring and trending of ageing effects:***

Cracking is one of the concrete ageing effects whose one of the degradation mechanisms is settlement. Cracks in concrete structures can be detected by visual inspections and is monitored to verify whether they are active or passive and to determine their root cause. For those actives, a crack monitoring programme is implemented aiming at analyzing their evolution, determining their root causes and taking corrective actions, if necessary. If settlement is proven to be one of the root causes of the cracks, a settlement monitoring programme is implemented[14].

The settlement monitoring programme aims at determining the values of the vertical displacements that the structure undergoes to evaluate its distortion that is compared with that established in the structural design basis of the plant. The settlement monitoring programme takes into account all relevant information that can lead to results with highest accuracy, and is carefully carried out to avoid the influence of extrinsic factors, such as temperature variation due to insolation, uncalibrated measuring equipment and human error.

The behavioral tendency of the structure is determined as the measurement campaigns of the settlement monitoring programme are carried out. If the structure presents a severe pathology concerning settlements, it is desirable to reduce the time interval between the measurement campaigns (section 4.6).

From section 4.1 up to 4.7, it is presented a settlement monitoring programme regarding a non-severe settlement case, based on the case of the Angra 1 NPP in Brazil (attribute 8).

***Topographic survey:***

The settlement monitoring programme is carried out through topographic survey which follow the local regulations. The topographic survey is performed by a specialized service provider company with minimum certified experience of 5 years.

The topographic survey equipment and accessories to be used depend on the characteristics of the service, and they are established by the corresponding local regulation.

Before the beginning of each measurement campaign, the service provider company presents the equipment calibration certificate, a copy of which is included in the reports of the campaigns.. The frequency of the equipment calibration is determined by the corresponding local regulations. For a good topographic surveying practice, the same measurement equipment are used in all campaigns. However, if its replacement is necessary, some requirements is met, such as:

* The next equipment has to be of the same class as the replaced one;
* The service provider company informs the NPP about the replacement of the equipment;
* The service provider company presents the calibration certificate of the equipment before the beginning of the measurement campaign;
* A copy of the calibration certificate of the equipment is included in the respective report of the campaign.

***Stainless steel settlement pins:***

Settlement pins are stainless steel tools used for the measurement of vertical displacements through topographic survey, whose shape and geometry aim at minimizing the measurement uncertainties. These pins are embedded into the concrete of the structures where settlement measurements are required and are preferably installed inside the structures to avoid the influence of the temperature variation due to insolation.

The points of the settlement pins installation is determined by the geotechnical engineering of the plant. Drawings comprising the floor plan and sections of the structure with their location is issued.

***Benchmark:***

The use of a deep benchmark is essential for a successful topographic survey, since it can avoid the influence of the temperature variation due to the insolation in the measurements, as well as physical damage to itself. The tip of a deep benchmark are at least 1.00 m within a sound bedrock and the top at least 0.20 m below the ground. The top of the covered concrete box, which provides the protection against physical damage, is at least 0.15 m above the ground.

***Groundwater level monitoring:***

The monitoring of the groundwater level is essential to the settlement monitoring programme since the groundwater level influences the behaviour of the soil in terms of settlement. For NPPs located near the sea, the influence of the tide, although generally neglectable as it is the case of the Angra 1 NPP in Brazil (attribute 8), is verified.

Groundwater level gauges is installed throughout the site of the plant to allow the measurements of the groundwater level that can be carried out using a sound level meter. Piezometers, which are used to measure the excess of pore pressure in a soil layer, may also be used to measure the piezometric groundwater level when the water pressure is hydrostatic. It is essential to start the monitoring of the groundwater level at least 3 months before the first measurement campaign of settlements.

It is proposed to perform three weekly measurements of the groundwater level at the same time of the day, preferably in the early hours of the morning. This task can be carried out by an employee of the plant that register and mark the local reference level adopted. This local reference level is corrected in relation to the benchmark through the topographic survey on the day of the next measurement campaign.Consequently, all the groundwater level values obtained in the interval between two subsequent measurements campaigns are corrected to be related to the benchmark.

After the beginning of the first measurement campaign until the last one, the measurement of the groundwater level can be performed twice a week at the same time as the previous ones by an employee of the plant, except on the days of measurement campaigns. On these days, the measurement of the groundwater level is a task under the responsibility of the topographic survey service provider company that has to carry out the measurements immediately after the measurement of the benchmark

A “Groundwater Level Monitoring Table” (GMT) spreadsheet is proposed and presented in ANNEX 1. This spreadsheet intends to gather all relevant information, such as weather condition, temperature, operating condition of the plant and heavy load movement inside the structure that are being monitored for settlement.

***Measurement campaigns:***

The measurement campaigns are carried out at fixed times, preferably early in the morning, under similar conditions, aiming at reducing the influence of the variability of extrinsic factors on the results.

During the measurement campaigns, the temperature is measured in the region of the benchmark, as well as near the settlement pins, and the values are registered on the “Settlement Monitoring Table” (SMT) spreadsheet proposed and presented in ANNEX 2.

Aiming at obtaining the effectiveness of the settlement monitoring programme, the participation and collaboration of the NPP unit is essential. As long as the settlement monitoring program lasts, the NPP unit provides specific reports informing the occurrence of each event that has altered its operating condition, such as the refueling outages.

In the case of the Angra 1 NPP in Brazil (attribute 8), the condensation cooling inlet and discharge channels, whose total volume corresponds to a loading of 23250 kN, pass through the basemat of the ETG Building. During the refueling outages, this channels are partially or totally emptied returning to the total volume condition when the unit is restarted. The volume reduction generates an unloading of the structure which is then reloaded by the volume increase until the channels are completely full again. Therefore, any volume change of these channels, which depends on the operating condition of the plant and may influences the structure vertical displacements, is reported.

In addition, the unit also reports each heavy load movement within the structures monitored for settlement that may lead to high eccentric loadings. The heavy loads can be, for instance, those transported by overhead cranes and those due to the dismantling of the turbogenerator for maintenance. In both cases, the plant provides the value of the load as well as drawings comprising floor plan and sections with its original location and new temporary storage area, including the dimensions of this area.

All these data provided by the plant inform the start and end dates and times, and they are available for the service provider company until the measurement campaign days. The service provider company has to include these informations on the SMT spreadsheet.

***Frequency of measurement campaigns:***

The following proposed frequency of the measurement campaigns, which regards to a non- severe settlement case, is:

* 2 campaigns twice a month, one every 15 days, for the first 6 months;
* 6 campaigns once a month, one every 30 days, for the next 6 months;
* 1 campaign every three months, for the next 12 months;
* 1 campaign every six months, for the next 12 months;
* 1 campaign in the next 12 months.

Totalizing 25 measurement campaigns in 4 full years. However, depending on the partial results obtained, it may be necessary to change this frequency.

***Reports issuance:***

Measurement campaigns reports are issued by the service provider company according to the timing schedule established in agreement with the plant. The data provided in these reports is analyzed and interpreted by the geotechnical engineering of the plant that also issue reports addressing the settlement behavioural trend.

1. ***Mitigating ageing effects:***

Although it is a condition monitoring programme, this AMP addresses some mitigating actions that may be required in cases of severe settlements.

According to attribute 6, the acceptance criterion for settlements is the maximum structural distortion. If the acceptance criterion is exceeded, it means that the settlement calculation is reevaluated and therefore the structural design are reevaluated for the new maximum distortion leading to the need of mitigating actions, such as installation or replacement of flexible supports for pipe and ducts, installation or replacement of joints between sections of pipes and ducts, and installation or replacement of penetration joints, or even corrective actions (attribute 7). The mitigating actions is defined jointly by structural and geotechnical engineering of the plant [15] and they is in accordance with the 10 CFR Part 50, Appendix B [16].

1. ***Acceptance criteria:***

The acceptance criterion for settlements is the maximum structural distortion, corresponding to the ratio of the difference between the maximum and minimum settlement values to the distance between their occurrence points. As the construction area of a nuclear power plant is very large, it is possible that the maximum distortion may not be the same for all structures, which would lead to different acceptance criteria, but each structure with its respective value. The maximum structural distortion values are provided in plant-specific design basis.

1. ***Corrective actions:***

If corrective actions are necessary, it means that it is a very serious case of settlement. The corrective actions may be soil treatment, structural reinforcement ,and even reconstruction.

The corrective actions are defined jointly by structural and geotechnical engineering of the plant [15] and they are in accordance with the 10 CFR Part 50, Appendix B [16].

1. ***Operating experience feedback and feedback of research and development results:***

This AMP addresses the industry-wide generic experience. Relevant plant-specific operating experience is considered in the development of the plant AMP to ensure the AMP is adequate for the plant. The plant implements a feedback process to periodically evaluate plant and industry-wide operating experience and research and development (R&D) results, and, as necessary, either modifies the plant AMP or takes additional actions (e. g. develop a new plant-specific AMP) to ensure the continued effectiveness of ageing management.

Operating experience case of the Angra 1 NPP in Brazil:

In Brazil, during the AEIA Pre SALTO mission to the Angra 1 NPP, the settlement issue of the Turbogenerator Building (ETG) came up.

According to [17], the settlements of the six Angra 1 buildings that compose the set of adjacent structures formed by the Turbogenerator Building (ETG), Fuel Building (ECB), Reactor Building (ERE), Safeguard Building (ESE), Auxiliary Building North (EAN) and Auxiliary Building South (EAS) were evaluated.

The foundations of these six buildings are basemats founded on different geotechnical materials. The ERE and ESE buildings are founded on sound bedrock and the ECB, EAN, EAS and ETG buildings are founded on a dense pure sand backfill overlying the sound bedrock. The geotechnical profile shows that beneath the ETG building and between the backfill and the bedrock there is a thin layer of residual soil. The ETG building borders the EAN, ESE and EAS buildings and is separated from them by expansion joints. The ETG overloads the foundation of the ESE and the EAN and EAS foundations overload the foundations of the ETG and ESE.

The foundation of the ETG building is a stepped basemat with a thickness of not less than 1.45 m and with the deepest base level at -10.75 m. From the level +5.15 m upwards there is an expansion joint, which extends up to the top of the building at level + 37.5 m. Its external dimensions are about 80 m × 36.5 m. From the top of the basemat, at level – 0.85 m, there is a new structure to support the turbogenerator, called turbogenerator table. Aiming at avoiding high vibrations in the entire building, expansion joints separate this table from the rest of the structure. Condensation cooling inlet and discharge channels pass through the basemat of the ETG building. The total volume of these channels is 2270 m3 of salt water, corresponding to a load of 23250 kN.

The settlement of the ETG building has been monitored since the end of its construction, i.e., after the application of all permanent and accidental loadings. As the basemat of the ETG building is founded on the sand backfill, settlements are not expected any longer after more than 30 years of lifespan. Therefore, it is very relevant to evaluate why it is still undergoing vertical displacements.

Calculations of uplift pressures and reloading stresses due to natural elevation and lowering of the groundwater level, respectively, were carried out and led to the conclusion that they cause the ETG building to undergo vertical displacements upwards (up-heave) and downwards (settlement). As the order of magnitude of the values of the uplift pressures and reloading stresses is too small if compared to the structure loads applied, the up-heaves and settlements occur within the elastic phase of the soil and, therefore, do not cause plastic strains, which are permanent. In addition to the calculations of uplift pressures and reloading stresses, as the Angra 1 NPP is near the sea, the influence of the tide was determined and disregarded as negligible.

Associated with the natural movement of the groundwater level, another fact that can lead the ETG building to undergo up-heaves and settlements is an unloading of its structure. This can occur during the refueling outages when the condensation cooling inlet and discharge channels that pass through its basemat may undergo partial or total volume reduction. For the restart of the plant, the volume of these channels is completed again leadind to the reloading of the structure.

Aiming at taking into account the natural variation of the groundwater level, the unloading and reloading of the ETG structure, and the different foundation supporting material, a 3D finite element model of the set of the six Angra 1 buildings mentioned above was constructed.

Although this model still needs some adjustments, it has proved the effect of the natural variation of the groundwater level and the unloading and reloading of the ETG structure in the settlements of the buildings, mainly in those of the ETG. This model also allows to consider the movement of heavy loads inside the ETG building and the eccentric loads that it generates, which will be carried out soon.

The next step is to carry out a groundwater level monitoring programme as well as a settlement monitoring programme of those six Angra 1 buildings, as proposed in this AMP. The values of the groundwater levels and vertical displacements obtained through these monitoring programmes along with the reports of the plant concerning its operating condition, which will allow taking into account the unloading and subsequent reloading of the ETG structure and the movement of heavy loads inside it, will be applied to the 3D finite element model that will provide analytical results of the buildings’ settlements to be compared with the actual field measurements.

Operating experience case of two units of a NPP in China:

In China, settlements were detected in two units of a NPP. The nuclear island buildings of this NPP are founded on soft rock.

The values of the settlements that occurred were different from those initially predicted leading to an increase in the frequency of measurements and the adoption of complementary measurements.

The influence of the settlements on systems and equipment was evaluatedand corrective actions were taken regarding the differential displacement of pipes that pass through adjacent buildings.

Settlement trends have been reevaluated using state-of-the-art analysis tools, and a peer review has been carried out by experienced experts.

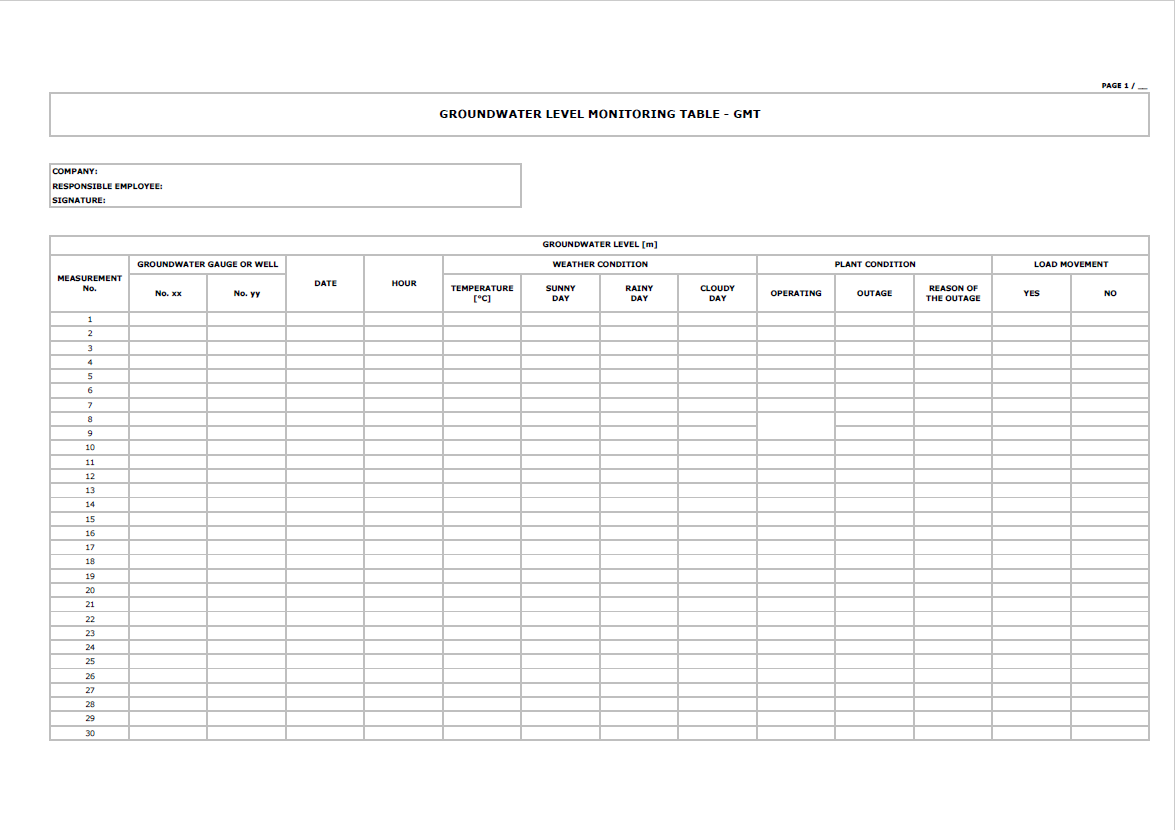
1. ***Quality management:***

A management programme is implemented to ensure the quality of administrative controls, data collection and record, quality of materials, procedures and reports, review and approval of processes, and personnel qualification that are in accordance with the local regulations.

**References**

1. AMERICAN CONCRETE INSTITUTE – ACI 349.3R-18, “Report on Evaluation and Repair of Existing Nuclear Safety-Related Concrete Structures”. January 2018.
2. ELETRIC POWER RESEARCH INSTITUTE – EPRI Report 1015078, “Plant Support Engineering: Aging Effects for Structures and Structural Components (Structural Tools)”. December 2007.
3. LAMBE, T.W. and WHITMAN, R.V., “Soil Mechanics”. John Wiley & Sons. 1979.
4. SCOTT, R.F., “Foundation Analysis”. Prentice-Hall, Inc..1981.
5. INTERNATIONAL SOCIETY FOR ROCK MECHANICS, “Basic Geotechnical Description of Rock Masses”. Int. J. Rock Mech. Min. Sci & Geomech. Abstr. Vol.18, pp 85 to 110. Pergamon Press Ltd. 1981.
6. HOEK, E., “Practical Rock Engineering”. E-book. 2006.
7. FLEMING, W.G.K., WELTMAN, A.J., RANDOLPH, M.F., ELSON, W.K., “Piling Engineering”. Surrey University Press. 1985.
8. SCHNAID, F., ODEBRECHT, E., “In Situ Tests and their Application to the Foundation Engineering” (In Portuguese). 2nd Edition. Oficina de Textos. 2012.
9. SAFETY REPORTS SERIES No. 82 (Rev. 2) - Ageing Management for Nuclear Power Plants: International Generic Ageing Lessons Learned (IGALL).
10. RICHART Jr., F.E., HALL Jr., J.R. and WOODS, R.D., “Vibrations of Soils and Foundations”. Prentice-Hall, Inc..1970.
11. ATKINSON, J.H., “Foundations and Slopes – An Introduction to Applications of Critical State Soil Mechanics”. McGraw-Hill Book Company (UK) Limited. 1981.
12. SELVADURAI, A.P.S.,   “Elastic Analysis of Soil - Foundation Interaction” - Developments in Geotechnical Engineering, Vol.17. Elsevier Scientific Publishing Company. 1979.
13. MARTINS, I.S.M., SANTA MARIA, P.E.L. and LACERDA, W.A., “A Brief Review about the Most Significant Results of COPPE Research on Rheological Behaviour of Saturated Clays Subjected to One-Dimensional Strain”. Proceedings of the International Symposium on Recent Developments in Soil and Pavement Mechanics, Rio de Janeiro, Brazil, 25-27 June 1997. A.A. Balkema/Rotterdam/Brookfield/1997.
14. ELETRONUCLEAR REPORT – BP/1/PGE/200022, “Programa de Monitoramento de Recalques do Conjunto de Estruturas de Angra 1 Composto pelo ETG, EAN, ESE, EAS, ERE e ECB” (In Portuguese). 2020.
15. THORBURN, S. and HUTCHISON, J.F., “Underpinning”. Surrey University Press. 1985.
16. UNITED STATES NUCLEAR REGULATORY COMMISSION-USNRC, 10CFR Part 50, Appendix B, Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants, National Archives and Records Administration, 2019.
17. ELETRONUCLEAR REPORT – BP/1/PGE/200021, “Análise de Recalques do Conjunto de Estruturas de Angra 1 Composto pelo ETG, EAN, ESE, EAS, ERE e ECB com Posterior Modelagem pelo Programa ANSYS” (In Portuguese). 2020.

**ANNEX 1 – GROUNDWATER LEVEL MONITORING TABLE (GMT)**



**ANNEX 2 – SETTLEMENT MONITORING TABLE (SMT)**

