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# Impact of climate change on the safety of the foundation zone of steel tanks

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**Abstract**

Climate change introduces the need to look at new issues in the safe operation of engineering structures, [1, 2]. Analysis for the past decade has shown the significance of the weather changes taking place and the effects in the form of periodic long heat waves causing heating of external surfaces combined with solar radiation can cause significant structural impacts. Intense rainfall causing increased penetration of water into the ground also proves to be an important issue in terms of the proper condition of foundation zones. Performed studies have shown that in unfavorable conditions can lead to defects in the foundation zones of steel tanks.

**Keywords:** war climate change, safety, steel tanks, settlement, leaching of soil

## 1 Introduction

Climate change introduces the need to look at new issues in the safe Operation of engineering structures. Extreme weather phenomena occurring in recent years have become the basis for an analytical assessment of the changes taking place. Analysis for the past decade has shown the significance of the weather changes taking place and the

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effects in the form of periodic long heat waves causing heating of external surfaces combined with solar radiation can cause significant structural impacts. Intense rainfall causing increased penetration of water into the ground also proves to be an important issue in terms of the proper condition of foundation zones. Performed studies have shown that in unfavorable conditions can lead to defects in the foundation zones of steel tanks. This is because the bottoms are founded directly on the ground at ground level or elevated above the adjacent terrain, so that the zone is not protected from atmospheric influences.

## 2 Identification of climate change

The weather changes observed in recent years, accompanied by the occurrence of extreme phenomena, are becoming a topical issue that requires proper interpretation. Long periods of dry days with high temperatures, interrupted by brief downpours, sometimes accompanied by hurricane gusts as well as tornadoes, are becoming a new problem in the country. Using measured data, an ongoing assessment of the occurring weather changes has been made for a city located in the North Podlasie Lowland - Bialystok. The long-term weather trends analyzed made it possible to conclude at the outset that climate change has not bypassed the city. The data of the Typical Meteorological Year (TMY), [10], which was compiled on the basis of source data from 1971-2000, shows that the average temperature in the TMY was 6.9°C. Of the 15 measurement years analyzed (the period from 2008 to 2022), only in 2010 was the average annual temperature lower than for the TMY. They ranged from 6.8°C to 9.3°C. In the measured data, apparently temperatures in the range of -25°C to -15°C and around 20°C to 22.5°C are more common than in the TMY. However, temperatures in the range of 2.5°C to 15°C are much less frequent than in the TMY data, Fig 1.

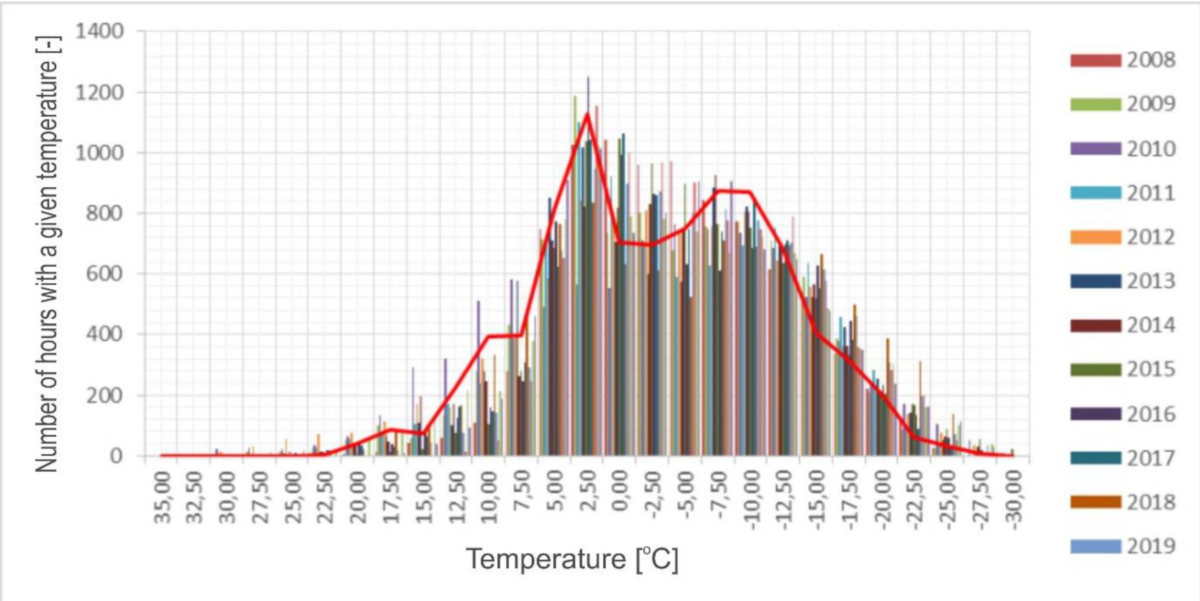


**Figure 1.** *Temperature histogram for the Typical Meteorological Year and the years 2008-2022; own compilation based on data [10] and [11]*

In terms of maximum annual temperatures, an upward trend is discernible. For the TMY, the maximum annual temperature value was 30.8°C. Between 2008÷2022, the maximum annual temperatures exceeded this value ten times. The highest of the annual maximum temperatures was recorded in 2015 and was 34.5°C, which is currently approaching $T(H)_{max}$ = 37.3°C. In contrast, the lowest of the annual maximum temperatures was 29.7°C and was recorded in 2009, Fig. 2. In the TMY, the minimum temperature was -17.6°C. For the fifteen measurement years analyzed, these temperatures ranged from -29.9°C to -9.3°C. However, in this case, too, there is a clear upward trend.

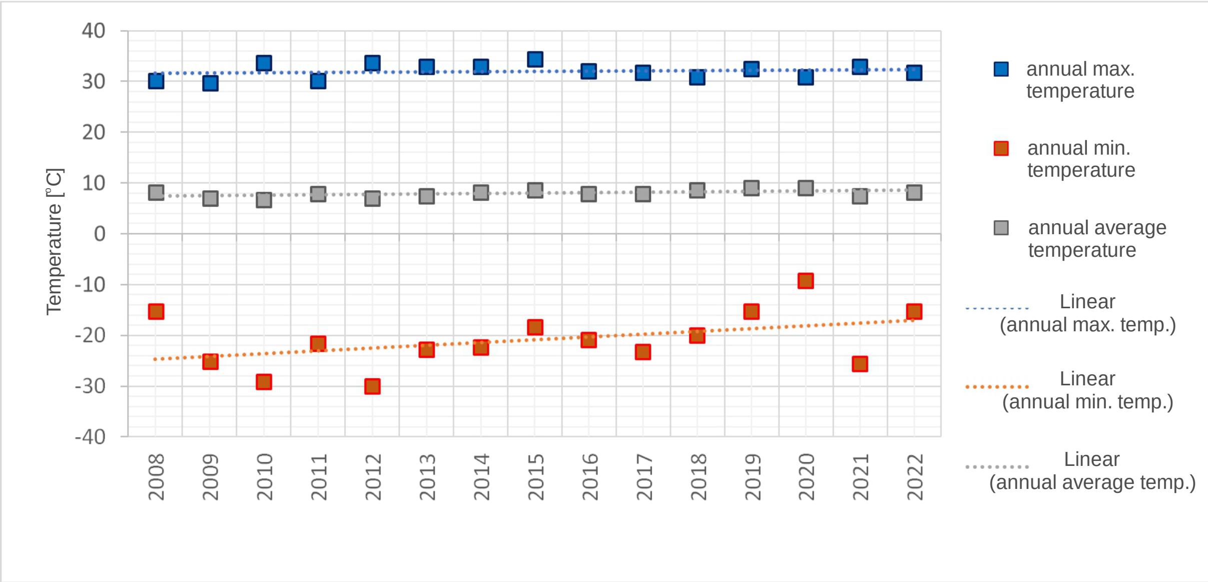


**Figure 2.** *Maximum, minimum and average temperatures in 2008÷2022; own elaboration based on data [11]*

An upward trend can also be observed in the number of hot days. Over the 2008÷2022 period, it can be seen both in the very marked increase in the number of days where the maximum temperature ranged between 30°C and 34°C, with a simultaneous recorded minimum temperature lower than 18°C, and in the case where the range of maximum temperatures is the same but the minimum temperatures are higher than 18°C. The first case, meets the requirements of degree 1 of heat danger, while the second meets degree 2 of heat danger, if the mentioned temperatures are recorded for at least two days. The 3rd degree of heat danger are cases where the maximum temperature exceeded 34°C for at least two days. Of the 15 years analyzed, such a case occurred only once, in 2015, Fig. 3. At the same time, there is a noticeable increase in the number of periods lasting two days, meeting at least the requirements for 1st degree heat warnings, Fig. 3. Of the fifteen years analyzed, the longest lasting heat waves reached a continuous length of 6 days and were recorded in 2015 and 2021. A heat wave lasting 4 days was recorded in 2014. In contrast, heat waves lasting three days each were observed in 2010, 2012 and 2018. In other cases, the length of heat waves was two days.

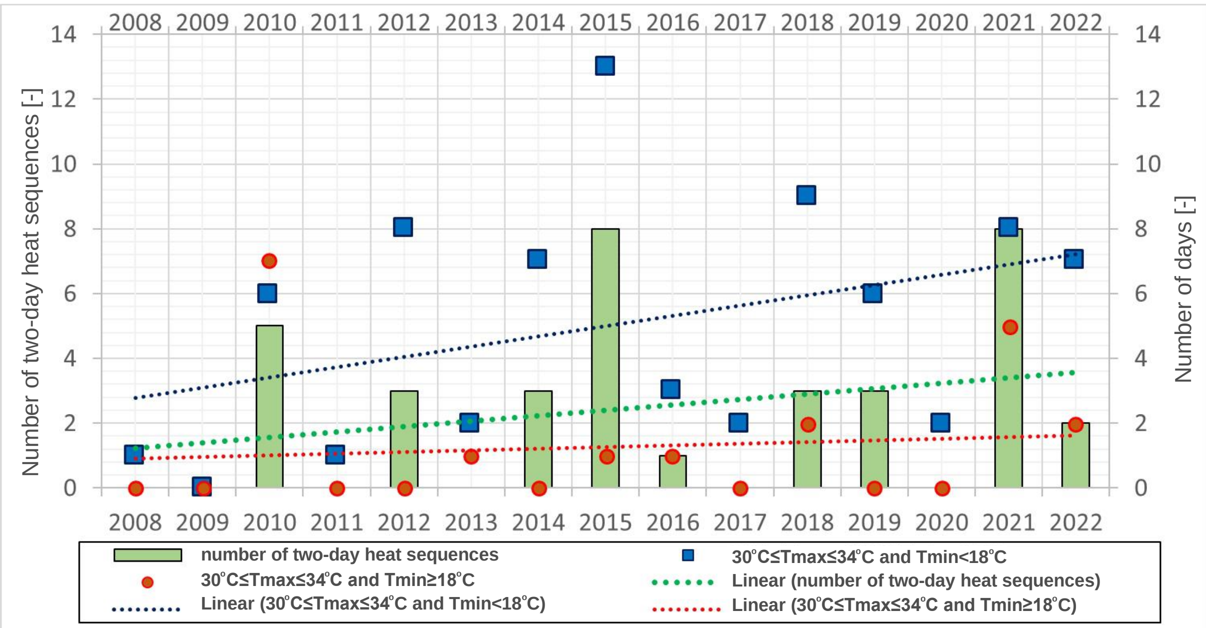


**Figure 3.** *Number of days meeting temperature limits for heat warnings; own compilation based on data [11]*

The existing climatic situation also exacerbates the risk of the so-called Urban Heat Island phenomenon in the Bialystok area, Fig. 4.

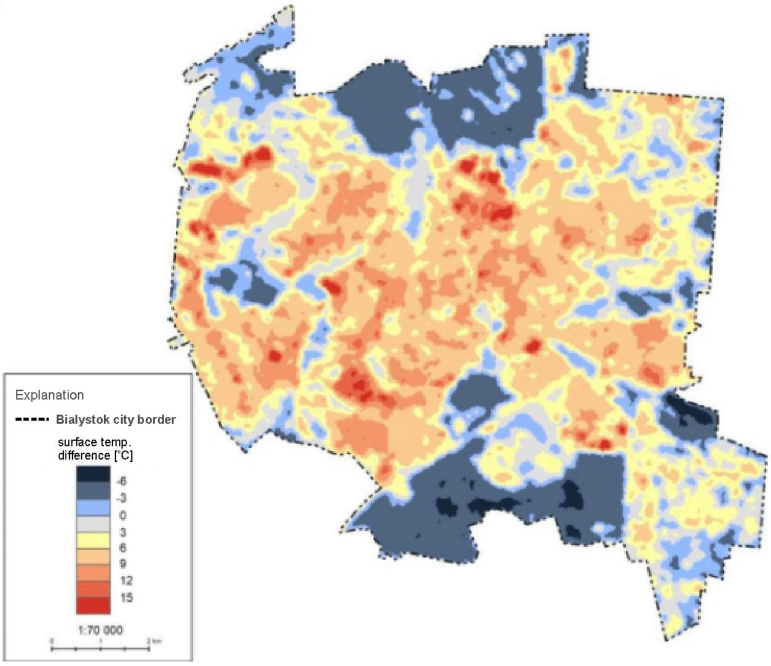


**Figure 4.** *Intensity of the Urban Surface Heat Island (12.06.2015) - differences between the temperature of the city and the surrounding area, (based on [10])*

Urban heat islands not only affect the lack of adequate living comfort for residents, but also directly affect technical infrastructure and its safe use [12]. Excessive insolation causes temperature accumulation, which can cause deterioration of technical facilities located in cities.

According to the probabilistic model PMAXPT [13], which is based on maximum precipitation information behind the Institute of Meteorology and Water Management IMWM, based on the AMP selection method, as the intensity of precipitation increases, the risk of excess precipitation increases, especially for short-term precipitation. The probability of a rainfall of about 90 $dm^3/s$□ha, for a five-minute rainfall, is about 99.9%. In contrast, for the same duration, the probability of rainfall of about 270 $dm^3/s$□ha, is about 50%. An analysis of 20 measurement years shows an increased range of annual precipitation totals [14], where maximum values reach more than 800 mm per year, while at the same time there are years with significantly less precipitation, from 450 mm. It is also noteworthy that for the period from May to October, gradual increases in daily precipitation are observed, which translates into an increase in the probability of local precipitation of 100÷130 mm, or even more. At the same time, a decrease in the amount of snowfall is recorded, with an extension of winter snow-free periods.

In the future, climate change is expected to worsen in the city area. Simulations developed within the framework of the Euro-CORDEX project indicate that by 2050 we can expect an increase by half in the number of heat days and the occurrence of heat waves, the occurrence of the phenomenon of so-called tropical nights, which is currently not observed at all, an increase of about 15% in the occurrence of intense precipitation, including torrential rains, and an increase of about 5% in total annual precipitation and periods of drought [9].

## 3 Tank foundation zone

The specific nature of the foundation of steel tanks, elevated above the ground surface, means that the effects of climate change have a direct impact on this type of construction. Cylindrical tanks for liquids are founded on a specially shaped subsoil, shaping their inclination in the direction of the shells. It is important to maintain the proper cooperation of the bottom with the upper layer of the subsoil, Fig. 5, under the conditions of adverse influences, accompanying climatic changes. The variety of solutions encountered for this zone is due to the type of subsoil at the foundation site and the technical possibilities of using direct foundation on the ordinate of the adjacent land. The contact zone is made using bitumen or a sand and bitumen mixture to protect the steel bottom from corrosion. In the absence of risk of corrosion, direct contact with the ground is encountered in the arrangement of tanks elevated above the ground surface. The layout of the layers and their thickness is determined from the conditions of uniform distribution of stresses and elimination of the process of bending of the tank bottom plates. The loads from the tanks are transferred uniformly in the middle zone, while in the area of the cylindrical walls the ground zone is affected by increased forces. This is due to the locally acting dead weight of the tank shells and overcaps.

Locally increased impacts are partially compensated for by extending the bottom plates beyond the edge of the cylindrical planes and reinforcing the connection to the bottom using additional steel profiles in the form of angles, for example. Another solution is to make a reinforced concrete ring in this zone located in the axis of the planes. Additional transfer of loads through the zone outside the inner bottom is conducive to the elimination of local stress concentration in the subsoil [3]. The prerequisite for the implementation of a correct technical solution is the individual determination of the impacts under the conditions of dead load in combination with external, environmental impacts. An important aspect that has not yet been widely analyzed may be the impact of daily high temperatures that persist for consecutive days or the occurrence of heavy rainfall. This is due to the possibility of changing the technical parameters of the substrate made with bitumen, since an increase in temperature directly results in a change in its characteristics, and in extreme cases can lead to its plasticization. Violent, intensive rainfall corresponding to torrential downpours causes water intrusion into the foundation zone, which, when cyclic conditions occur, can result in the effect of leaching of soil from the bottom fringe zone [4].

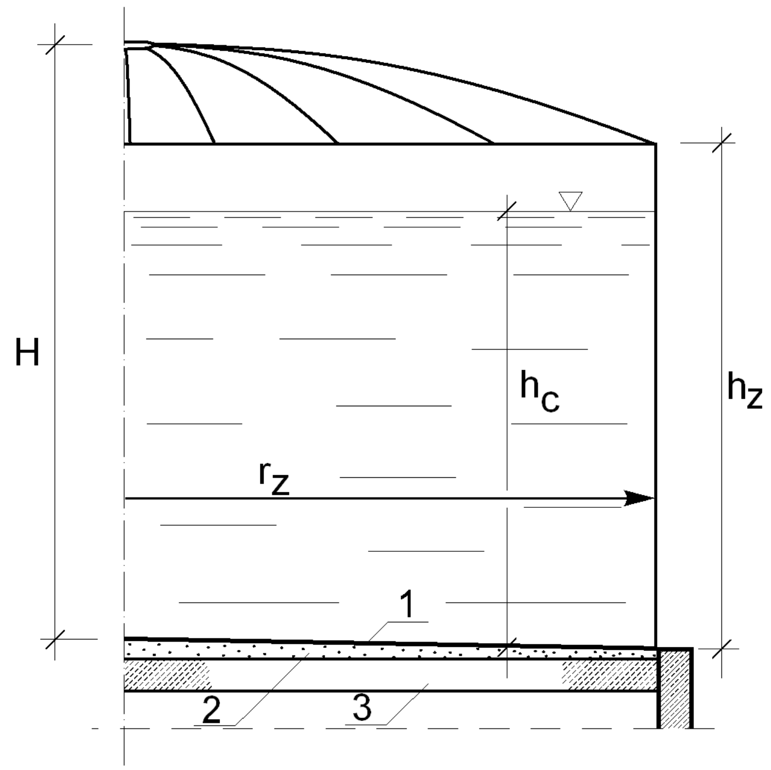


**Figure 5.** *Foundation of cylindrical tanks; 1 - bottom of tank; 2 - insulation layer - sand, sand-bitumen or bitumen pad; 3 - native soil/reinforced concrete slab*

## 4 Environmental impacts in the relationship of climate change

Climatic influences cause cyclic thermal changes during many years of use, resulting in changes in the temperature of the stored medium in the tanks, as well as changes in the state of stress in the structural area. Particular importance in the field of thermal impacts occurs in relation to uninsulated tanks through the simultaneous impact of increased external temperatures in correlation with solar processes. Due to the implementation of tanks in the form of a battery, possible shielding obstacles from direct sunlight may be neighboring tanks. The initial activity is to determine the location of the facilities in relation to the sides of the world and to determine any mutual exposure restrictions that occur at certain times, resulting in a reduction in the effects of shell heating [5, 6].

The calculation of the temperature load values of mantles and roofs is performed based on the provisions of standards [7], [8]. The norm parameters can be verified by taking actual environmental measurements. Ambient temperature $T_{out}$ and exterior surface temperature *Tmax* are measured during the work. Archival values of ambient temperature can be obtained from databases of weather stations located at sites of permanent weather monitoring. The specificity of the impacts on steel tanks requires consideration of the coupled issue of temperature distribution also in the area of the stored medium, Fig. 6.

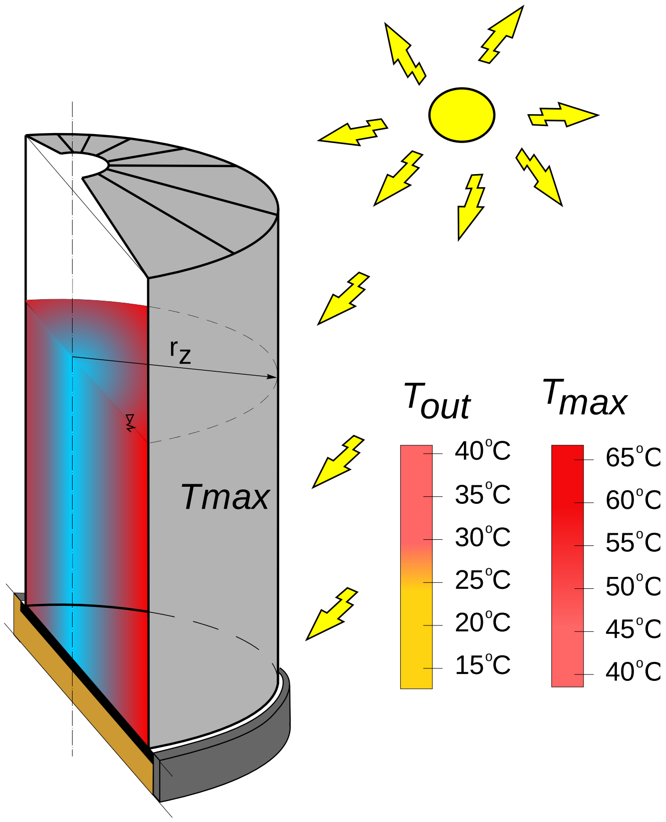


**Figure 6.** *Thermal impacts due to the persistence of hot days in the summer along with intense sunshine*

On summer days, the surface of the steel outer shells undergoes heating, and the temperature rises to values close to the ambient Tout, facilitated by the observed reduction in their diurnal fluctuations. The accumulated medium, also undergoes a process of heating, the intensity of which depends on the diameter of the tank $r_z$ and the filling height $h_c$. The influence of solar radiation causes the temperature of the shells to rise above the ambient temperature while causing uneven heating of the accumulated medium. This is due to the fact that steel surfaces, exposed to solar radiation, transfer heat directly to the medium accumulated at their surface. The lack of mixing or circulation promotes locally different thermal states also within the foundation zone.

Realizing the calculation of impacts in the form of insolation, the values of maximum temperatures that occur on the shells located on the southwest and west sides are determined. The minimum values occur on the north side and depend on the value of the radiation absorption coefficient. Light-colored surfaces are characterized by a coefficient value of 0.5 and increases to a value of 0.9 for dark colors. The procedure for determining the temperature on the outside of $T_{out}$ structures, taking into account the processes of insolation according to the provisions of the standards, does not properly reflect the commonly occurring thermal states in the near-surface zones, since the temperature on the outside is generally significantly lower than the values identified directly at the surface of the elements.

The peculiarities of cylindrical tanks indicate that the greatest influence of insolation processes resulting from the sides of the world, i.e. the southwest, will cover practically every time half of the entire lateral surface. For facilities located in areas with a maximum temperature in the shade of $T_{out}$ = 38ºC, seated at an ordinate of 135 meters above sea level, temperature distributions were determined for light-colored and silver-gray surfaces, using the provisions of the standard [7]. The calculated values of $T_{max}$ temperatures for the summer season are summarized in Table 1.

*Table 1. Calculated temperatures $T_{max}$ in the summer time*

| **Surfaces on the southwest side** | Standard PN-EN 1991-1-5:2005 |
|---|---|
| Light-colored surfaces | 55.3ºC |
| Silver-gray surfaces | 67.3ºC |
| **Surfaces on the northeast side** | |
| Light-colored surfaces | 37.3ºC |
| Silver-gray surfaces | 39.3ºC |

## 5 Assessing the impact of climate change on direct foundation

The recorded hot weather, lasting for a period of 6 days, results in an increase in daytime temperatures on the outer surfaces to a value close to 60ºC, which was taken as representative in the process of evaluating the behavior of the substrate located directly under the bottom of the reservoirs. An attempt was made to evaluate the condition of the substrate layer made with bitumen located directly at the outer edge of the tank bottom. The technical parameters of bitumen in terms of softening temperature are important in the evaluation process. According to PN-EN 12591, softening depends on the type of material and begins at 43÷51ºC for lower grades and 55÷63ºC for higher grades. Heating of the foundation zone to values above the softening temperature of bitumen will each time lead to a change in the state of the mass to visco-plastic.

Exceeding the limiting stresses for the bitumen layer due to thermal effects during the summer can result in the mass being squeezed out from under the bottom of the tank and, consequently, swinging it out of the vertical axis, Fig. 7.

**Figure 7.** *Foundation of the tank on the bituminous mass; 1 - steel gutter, 2 - extruded bituminous mass, 3 - reinforced concrete ring*

Another problem accompanying climate change is periodic heavy rainfall causing impeded drainage of rainwater from the foundation zone which results first in a rise in the level of accumulated water and then in its penetration under the bottom of the reservoirs. Subsequent lowering of the moisture level and drying can lead to leaching of soil particles and, with the intensity of the process, also to the formation of voids and lack of contact between the bottom and the ground, [15], Fig. 8.


**Figure 8.** *Sand foundation zone of the tank; 1 - steel bottom of the tank, 2 - washed sand from the ground, 3 - reinforced concrete slab*

Climate change is resulting in an intensification of extreme weather events, where technical issues relating to the foundation zone are proving important:

- changes in the parameters of the bituminous layer underneath the foundation caused by the persistence of several days of hot weather with intense sunshine;
- leaching of soil from the foundation space due to intense rainfall causing heavy penetration of water into the ground.

## 6 Monitoring of the foundation zone

Periodic inspections carried out annually are designed to detect possible damage and defects in the structure. Performed, as a rule, using macroscopic techniques, they do not allow identification of the initial stages of damage to foundation zones. Secondary effects of changes in the ground are tilting of the vertical axis of tanks, which can be detected using surveying techniques and currently using 3D laser scanners. Available technologies allow data recording with the following devices: ground-based, mobile and aerial. Early detection of defects in a facility will enable appropriate preventive measures to be taken, which may include limiting the amount of accumulated medium and, in extreme cases, emptying the tank for the expected negative thermal effects.

Terrestrial laser scanning is performed by setting fixed control points and monitoring their position at established time intervals. This way of control, allows to determine the degree of displacement of object elements between successive observations. With each measurement, the laser scanner non-invasively records the so-called point cloud. This is a collection of data in the form of millions of points with specific XYZ coordinates, along with information about the intensity of the laser beam's reflection from the object I [16]. Each cloud is a geometric representation, physically existing object, in virtual space. Laser scanning also makes it possible to obtain information about, for example, uneven settlement and deviation from vertical of an object. It is also possible to prevent the consequences of negligence that result from excessive deformation of structural elements [17, 18].

Fig. 9 shows an example of registering with a laser scanner the settlement of a reservoir and its deflection from vertical as a result of rainwater. The first measurement was recorded in March (gray-yellow point cloud). Then the measurement was repeated in November of the same year and a cloud marked in red was registered. Rainwater was getting under the tank, causing it to collapse under its own weight and the liquid stored in it. The result was a 2.7-degree tilt of the object from the vertical.

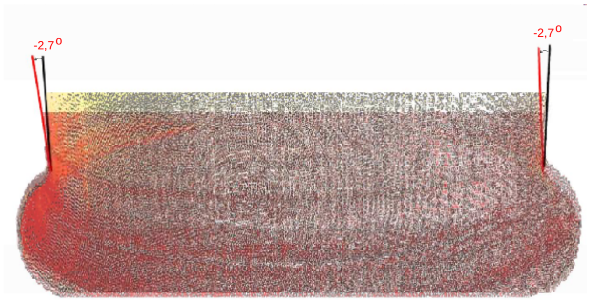


**Figure 9.** *Measurement of deviation from vertical of water tank presented by superimposing two point clouds*

Proper execution of monitoring measurements, gives the opportunity to react quickly to the occurrence of disturbing changes in the foundation area, which also prevents the loss of stability of the facility. The implementation of rapid measurements, the countermeasures taken allows you to maintain the infrastructure of the reservoirs in proper technical condition and ensures the safety of its use.

## 7 Conclusion

Climate change places new demands on the Users of engineering structures. It becomes necessary to interpret the adverse effects of atmospheric conditions on the state of safety because, as shown, they can cause damage to foundation zones and, consequently, the need to take them out of service.

Reducing the negative temperature rise in the foundation area of steel tanks is possible to achieve by performing protective coatings in bright colors that reflect solar radiation. Reducing the direct impact of external temperatures during periods of ezpisodic high temperatures occurring on consecutive days, in turn, can be achieved through the use of insulating cladding, which will also act as a barrier from the effects of solar radiation. During summer periods with forecasted increased insolation and sustained high daytime temperatures, it would be advisable to reduce the level of stored medium on an ad hoc basis so as to limit impacts on the foundation zone in a controlled manner. Each arrangement of cooperating with the ground should be correlated with the actual state of affairs and the existing technical solutions of the foundation zone.

During periods of days that significantly deviate from the TMY, it proves necessary to intensify the inspection of engineering facilities by the Users' technical services, aimed at early detection of possible defects, also using laser scanning technology.

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