

SELECTED ASPECTS OF THE DESIGN AND CONSTRUCTION OF REINFORCED CONCRETE SUNK WELLS

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ABSTRACT

The article provides basic information on the design and construction of sunk wells. Sunk wells are engineering structures commonly used in construction, particularly under difficult soil conditions or when construction sites have a small area. Sunk wells are made using the “cut and lower” method, which means that the first segment to be lowered is equipped with a cutting-edge section (bottom blade) that cuts into the soil and the structure sinks into it. In design, it is necessary to take into account the phased execution of these structures and their spatial work. The article presents the loads working during the construction and operation of sunk wells, as well as the assumptions and guidelines for static calculations and dimensioning. When the sunk well steining is significantly high (the well is embedded deep), concreting and lowering are most often performed in two or three segments. The article describes the subsequent steps taken during the implementation of sunk wells, constantly changing static diagrams and the method of adopting them in calculations. It also presents the method of lowering sunk wells with possible implementation difficulties. The article is supplemented with exemplary drawings of the steining reinforcement, cutting-edge section and bottom plate of the well and the photos of selected realizations.

Key words: sunk wells, cylindrical tank, rectangular tank, cutting-edge, concrete plug, sinkability

INTRODUCTION

Reinforced concrete sunk wells are frequently used in general, industrial, water-drainage construction as well as in building of engineering facilities for sewage treatment plants. Sunk wells with small cross-sectional dimensions, primarily circular, have been used for many years as wells for groundwater intake in farms. After filling the structures with sand or lean concrete, they can serve as an element of building foundations. Sunk wells with a larger cross-section are made in order to obtain rooms for the installation of equipment for water pumping stations or hydropower plants or various types of machines and devices. The term sunk well should be understood as a structure consisting

of walls that end with a cutting-edge (bottom blade), with a concrete plug and a bottom plate made at a later stage. Most often, sunk wells with a circular or rectangular cross-section (polygonal, oval or other) are made of reinforced concrete. Under their own weight, while simultaneously removing the soil from the inside of these structures, they sink into the ground (Szymczak-Graczyk, 2021). Examples of horizontal cross-sections of sunk wells are shown in Figure 1, and the method of their lowering in Figures 2 and 3.

The choice of using sunk wells may be determined by difficult ground and water conditions in the area of sunk well foundations or the limited space during their construction, preventing the execution of wide excavations.

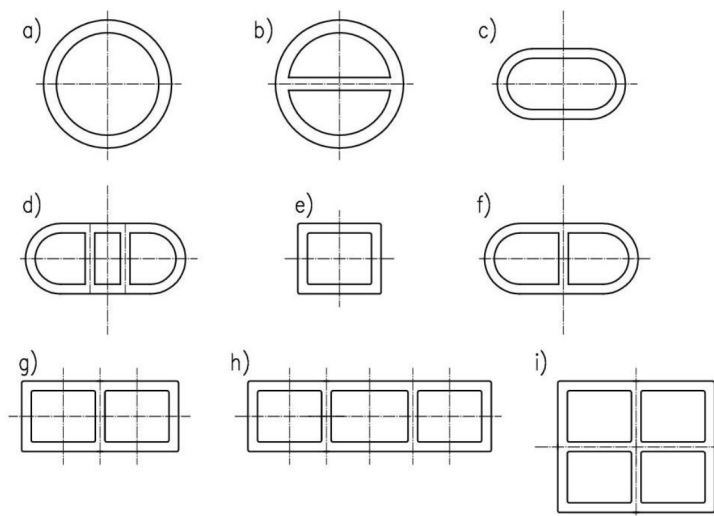


Fig. 1. Horizontal cross-sections of wells: (a) single circular, (b) twin circular, (c) oval, (d) three-chamber oval, (e) square, (f) twin oval, (g) twin rectangular, (h) three-chamber rectangular, (i) four-chamber rectangular (Płaskowski & Roman, 1968)

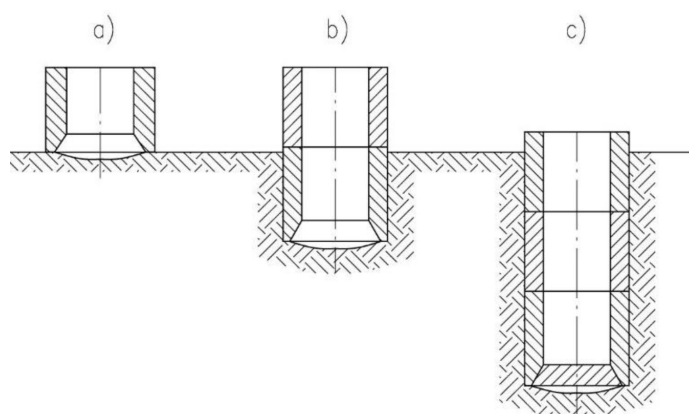


Fig. 2. Scheme of the sinking operation: (a) steining before sinking, (b) steining during sinking, (c) steining after sinking (Rossiński, 1966)

The undoubted advantages of using sunk wells include the relatively small volume of earthworks required and the possibility of their implementation without lowering the groundwater table. Sunk wells with a circular cross-section, under normal conditions of execution and operation, work as a thick-walled cylinder, evenly compressed, and as such, they do not pose any major difficulties for static and strength calculations. The necessity to take into account both compression and bending in static and strength calculations may appear for wells with larger diameters, as well as for the

analysis of sunk wells that tilt during lowering. It should also be borne in mind that during the process of lowering, wells with circular or rectangular cross-sections act like pipes with free ends, and after making their bottom plug, the lower end of the pipes changes into a freely supported part, thus creating a cylindrical or cuboidal tank (Szymczak-Graczyk, 2021). Consequently, sunk wells should be calculated with methods that take into account their spatial nature as well as changing static diagrams (Mikołajczak & Gołaś, 1972; Buczkowski & Czwójdziński, 1985; Buczkowski, 1988, 1989; Bucz-

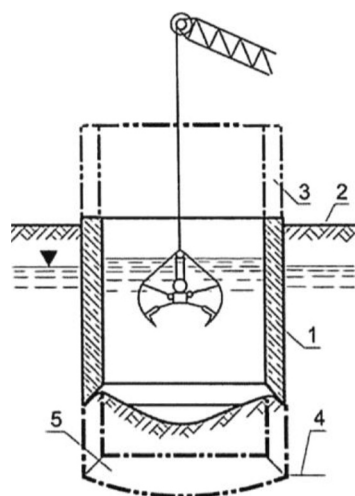


Fig. 3. Well during the sinking operation: 1 – steining, 2 – ground level, 3 – superstructure of the well after sinking of the first segment, 4 – foundation level, 5 – bottom plate made after complete sinking (Płaskowski & Roman, 1968)

kowski, Mikołajczak, Sroka & Wosiewicz, 1989; Buczkowski, Czwojdzinski & Staszewski, 1991).

The use of simplified methods in static calculations, consisting in “cutting out” of the horizontal frames from the structure and determining for them their bending moments, or considering the well structure as composed of individual slabs and then calculated, may – in many cases – lead to erroneous estimation of the values of bending moments occurring in the steining. Descriptions of design using simplified methods can be found in scientific papers published many years ago (Mikołajczak & Gołaś, 1972; Rossiński, 1976; Czarnota-Bojarski & Lewandowski, 1978; Mołoniewicz, Sędzikowski & Bonikowski, 1979). Examples of solutions and design tables were provided for instance by (Ulickij, 1959; Timoshenko & Woinowsky-Krieger, 1962; Stiglat & Wippel, 1973; Szadurskij, 1976; Bareš, 1979; Buczkowski, 1988). In recent years, the Polish literature has expanded to include several publications regarding sunk wells calculated with more modern approach (Halicka & Franczak, 2013; Pisarczyk, 2019; Halicka & Franczak-Balmas, 2020; Szymczak-Graczyk, 2021). Nowadays, 3D calculations using the finite element method supported by specialised software

are common and should not be of any difficulty for designers. However, it is important to remember to verify them, i.e., with the help of the design tables by Buczkowski (1992) – prepared on the basis of calculations made with the finite difference method.

WORKING LOADS IN THE CONSTRUCTION AND OPERATION OF SUNK WELLS

Sunk wells are underground structures; therefore, they are subject to the following loads:

- active soil pressure acting on the steining during lowering,
- resting pressure acting on the lower part of the steining to the offset during lowering and on the entire well during its operation,
- soil resistivity in the event of tilting during lowering, acting on part of the steining,
- groundwater pressure acting on the walls and the bottom of the well,
- groundwater buoyancy,
- soil resistivity under the bottom of the well, from the total weight of the structure (without reducing the friction on the side surface of the well and the buoyancy of groundwater),
- friction of the steining against the soil during the stage of lowering (friction force directed vertically upwards, which must be overcome in the process of lowering the well) or in the case of buoyancy (friction force directed vertically downwards, counteracting the buoyancy force),
- thermal load due to temperature or temperature changes of stored wastewater in facilities (tanks) used in wastewater treatment plants.

The value of soil pressure acting on the steining depends on the consistency and type of soil, designed depth of sunk wells, displacement (deflection) of well walls, backfill load as well as the level of groundwater table.

Generally, during the process of lowering sunk wells, the soil in the area of the steining loosens, which is caused, inter alia, by the use of offsets in the cutting-edge section. When this happens, the steining above the offset is affected by active soil pressure, and the part below by resting soil pressure. If the steining tilts during lowering, some elements of well walls may be

subject to soil resistivity (Szymczak-Graczyk, 2021). The determination of geotechnical parameters such as internal friction angle, soil cohesion, volumetric weight is one of the key stages of geotechnical design carried out in accordance with Eurocode 7 (European Committee for Standardization [CEN], 2004b), i.e. PN-EN 1997-1:2008 standard (Polski Komitet Normalizacyjny [PKN], 2008).

ASSUMPTIONS AND GUIDELINES FOR STATIC CALCULATIONS AND DIMENSIONING OF SUNK WELLS

The key issues to be considered when designing sunk wells are:

- proper sinkability,
- buoyancy stability when implemented in irrigated soil,
- design with regard to the strength of a steining,
- design of reinforcement of a bottom blade,
- design of a concrete plug and a reinforced concrete bottom plate.

The method of implementation of sunk wells consists in making a steining (external walls) in a levelled ground (soil), in a possibly lowered area. Then by removing the soil mass from the inside of the well, the structure should sink into the soil under its own weight. During the process of lowering, well walls are affected by lateral soil pressure and dependant friction forces of the steining against the soil. To ensure that the well is sinkable, its weight, taking into account buoyancy forces in irrigated soils, must be greater than friction forces on the side surface, which is expressed by Formula (1):

$$Q - W > T. \quad (1)$$

where:

- Q – total weight of the lowered well segment during lowering [kN],
- W – weight of water displaced by well walls (water buoyancy) [kN],
- T – total friction force of the steining of the lowered well segment against the soil [kN] (Szymczak-Graczyk, 2021).

In the process of lowering sunk wells, the required weight of the steining to overcome the friction of concrete against the soil can be significantly reduced by using a thixotropic suspension (Puścikowski, 1973).

If the well is implemented in irrigated soil, it should be checked whether its weight resists water buoyancy. If the well with a bottom plug is too light, the buoyancy of groundwater may cause it to flow out (overturn). The buoyancy stability should be verified after the water is pumped out from the inside of the tank, with the tank empty, and without any additional devices inside increasing its weight.

When considering the ultimate limit state of displacement (UPL) in accordance with EC7, it should be verified whether the design value of combination of vertical destabilizing actions, both constant and transient ($V_{dst,d}$) is less than or equal to the design sum of stabilizing values of vertical constant actions ($G_{stb,d}$) and the design value of additional resistance counteracting displacement (R_d), expressed by Formula (2):

$$V_{dst,d} \leq G_{stb,d} + R_d, \quad (2)$$

where:

- $V_{dst,d}$ – design value of destabilizing vertical actions on the structure,
- $G_{stb,d}$ – design value of the permanent vertical stabilizing action to verify displacement,
- R_d – design value of the additional resistance against displacement; the additional resistance against displacement can also be treated as a stabilizing vertical permanent action ($G_{stb,d}$).

Protection against outflow (displacement) of sunk well segments is achieved by appropriate thickening of a bottom plug or the use of an anchor ring. The anchor ring is used to balance the buoyancy forces of the soil weight lying on the circumferential ring of the well (Buczowski, 1991b).

When the steining is relatively high (the well is embedded deep), concreting and lowering are most often performed in two or three segments with a segment height of approx. 3–4 m. **Static calculations** should include the requirements of each individual implementation phase. Considering sunk wells con-

structed in two stages, the course of their realisation is as follows:

- Phase 0 – preliminary works, including preparation of back-up facilities and the site, construction of the lower segment of the well, which will be implemented as first. After lowering, the structure is loaded “preliminarily” in its lower segment. The sunk well deflects, cross-sectional forces due to the working loads act and only after this stage the construction of the upper part of the well can begin. During the entire process of lowering the well, the upper and lower edges are free. After making the bottom plug underwater, the static diagram changes – the boundary conditions on the lower edge change. Sunk wells with a rectangular cross-section change into a box system, and sunk wells with a circular cross-section form cylindrical tanks with a freely supported lower edge. After the water has been pumped out from the inside of the well, the structure is additionally loaded in the form of water pressure from the outside. Assuming that the well is concreted in two stages, three phases should be considered in static calculations, each of which has to take into account the spatial nature of the structure.
- Phase I – the state of lowering the first segment of the well. The load in the form of soil pressure is transferred to the steining, calculated regarding soil irrigation and backfill load. The bottom edge finished with a cutting device and the top edge are free.
- Phase II – the state of further lowering the well with the upper segment of the steining concreted in. By taking into account deflections and cross-sectional forces generated in Phase I, the load in Phase II should be assumed as soil pressure. The horizontal edges of the well are free.
- Phase III – the well is completely lowered, with a concrete bottom plug and the water pumped out from inside. The load is identical as in Phase II, increased by water pressure, acting from outside, with the bottom edge of the well freely supported and the top edge free.

In design practice, in order to verify the load-bearing capacity of sunk wells in the lowering phase, usu-

ally the selected horizontal elements of the steining are calculated. Such an element is considered a ring or a closed frame affected by soil pressure. For sunk wells treated as a system composed of single plates, calculations can be made using the table solutions for plates with two opposite edges fixed and the other two free. After the well is completely lowered and the bottom plug is made, the bearing capacity condition is verified by treating the structure as a cylindrical or rectangular tank, in which the lower edge is freely supported, and the upper edge is free. However, the most reliable solutions are obtained by analysing the tank in three dimensions i.e., by the finite difference method or the finite element method using specialised engineering software.

The cutting-edge section made in the lower part of the steining is designed to facilitate the penetration of the steining into the soil, ensure the vertical direction of the well (without excessive deviations) when removing the soil from inside, protect the walls from damage by obstacles encountered during lowering.

The cutting-edge section of the well should be verified for forces that may occur during the process of lowering i.e., it should be verified for vertical bending, treating it as a cantilever fixed in the A-A section (Fig. 4). Calculations of bending resistance in relation to the cutting edge assume that the well is lowered to its full depth and consider two options for forces that cause bending. The first option takes that the cutting edge does not rest in the soil (it is excavated under) and it is subject to bending due to soil pressure from outside (Fig. 4a). The second option recognizes that the cutting edge is embedded in the soil and it is affected by vertical resistivity R_1 and R_2 and the horizontal resistivity component (V) of the tilted part of the cutting edge. The literature also provides the recommendation for calculating the horizontal bending of the cutting edge due to soil pressure distributed evenly on the outer perimeter of the well and due to soil resistivity (V) applied evenly from inside, acting on the tilting surface of the cutting edge.

The concrete plug is made when the steining has already been lowered to the designed depth. Its concreting is most frequently conducted underwater. The plug is designed to transfer the total hydrostatic thrust

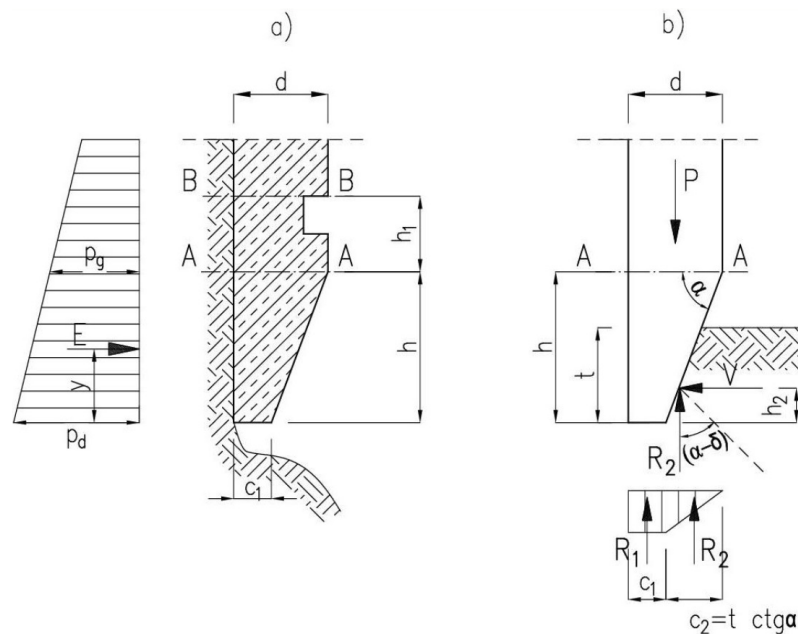


Fig. 4. Static load diagrams for the cutting-edge section: (a) when the soil under the cutting edge is excavated, (b) when the well cuts into the soil with the cutting edge (Płaskowski & Roman, 1968; Buczkowski, 1991a; Szymczak-Graczyk, 2021)

that will act on the bottom of the structure after draining the water from inside. Calculation of the required thickness of the plug, assuming that the well does not longer descend under its own weight (removal of the ground from the inside of the well has been completed, support of the base of the cutting edge against the ground and friction forces of the steining against the ground are large enough to keep the well in a certain position), is made adopting the calculated load acting on the plug as a uniform hydrostatic thrust load from underneath, minus the weight of the plug. The reinforced concrete plate resting on the concrete plug is calculated for the soil resistivity load from the total weight of the structure including devices and taking into account operational loads, without frictional forces on the side surface of the steining and water buoyancy. For this load, bending moments are calculated, the plate thickness is determined approximately, and the usable height of the plate is taken along with the covering required.

Calculations of the necessary reinforcement of sunk well elements should be made in compliance with Eurocode 2 (CEN, 2004a), whereas the minimum class

of concrete should be determined taking into account the exposure class according to PN-EN 206-1:2003 standard (PKN, 2003). For the reinforcement of the structure in accordance with the Eurocode 2 requirements, only ribbed and weldable steel bars, the yield strength of which ranges from 400 to 600 MPa, can be used. Figures 5–7 show examples of the reinforcement of sunk well elements.

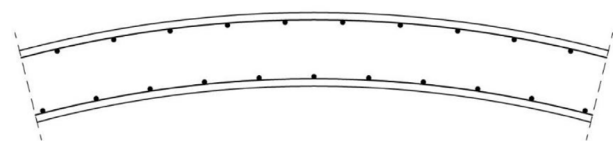


Fig. 5. Example of reinforcement of the wall of the well (Szymczak-Graczyk, 2021)

THE PROCESS OF LOWERING SUNK WELLS

There are three types of conditions in which sunk wells are lowered and the excavated material is extracted:

- in non-irrigated soil,
- in irrigated soil, but in conjunction with pumping water out,

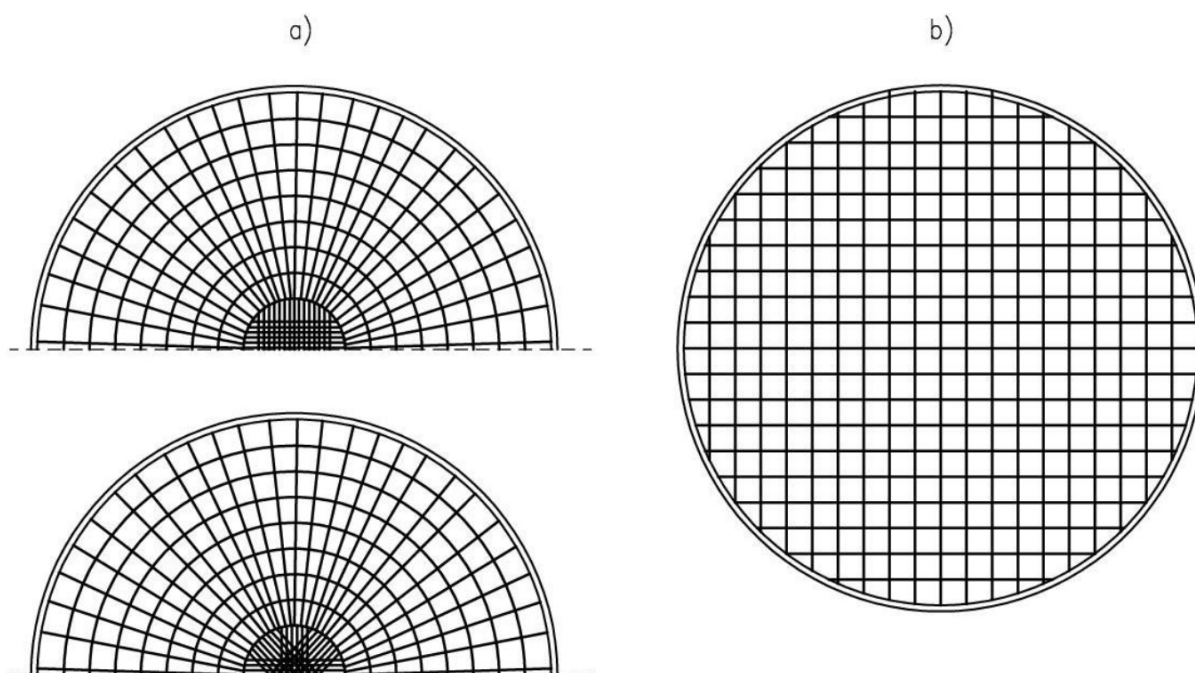


Fig. 6. Examples of possible arrangement of the reinforcement in bottom plates of circular wells: (a) radial reinforcement of the bottom plate freely supported on its perimeter, (b) cross reinforcement (Szymczak-Graczyk, 2021)

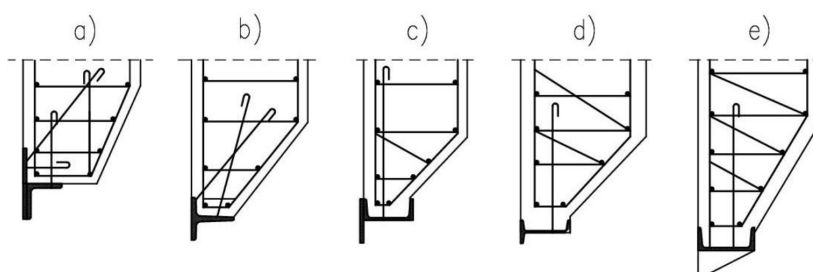


Fig. 7. Cutting edge sections of wells: (a) cutting edge with the shelf protected by steel sheet, cutting edge made of metal sheet and L-beam, (b) cutting edge made of half I-beam or T-beam, (c) cutting edge and protection of the shelf made of metal sheet and C-channel, (d) cutting edge reinforcement with I-beam and the shelf cut, (e) welded reinforcement of the cutting edge shelf with I-beam and metal sheet with triangular diaphragms (Szymczak-Graczyk, 2021)

– in irrigated soil, but without pumping water out when lowering the well, using the underwater extraction method.

Under all the above soil conditions, sunk wells can be lowered with the use of a thixotropic suspension. The thixotropic suspension layer around the steining is obtained by pouring the suspension into the space between the steining (above the offset) and the soil.

The use of a thixotropic suspension (bentonite, clay) reduces the friction forces between the steining above the offset and the soil by up to 80% (Płaskowski & Roman, 1968).

For most sunk wells, their construction is not possible without interruptions in concreting (segmentation). This is due to the concreting and lowering sunk wells divided into segments with a height of approx.

3 to 4 m. Each discontinuation of concreting requires the structure is still monolithic, and its walls are tight. Most often, the interval between concreting successive segments lasts from 2 to 4 weeks and depends on the ambient temperature, the time necessary to obtain appropriate concrete strength parameters and the time needed to lower a given segment.

As might be expected, the reinforcement keeps its continuity (it is not interrupted) during these working breaks.

Difficulties that may occur when lowering the steining of sunk wells are the remains of old buildings, boulders or tree trunks found in the ground. In this case, suitably heavy chisels with a weight of up to 50 kN should be used for shredding tree limbs or heavy chisels with a weight of up to 50 kN for crushing stones. Crushed stones are pulled up using winches (Szymczak-Graczyk, 2021).

Particular attention should be paid to whether the sunk well is in a vertical position or it is not displaced horizontally. Deviations from the vertical of more than 10 cm and displacements in the horizontal plane of more than 2 cm should not be allowed. Vertical alignment should not be quick and immediate, but gradual, as the structure goes deeper. The simplest and most frequently used method of bringing the well to a vertical position is the more intensive soil extraction from the inside of the well from the side where the cutting edge sunk shallower, and at the same time slower extraction from the opposite

side. Soil extraction only from one side of the steining should not take place, since the applicable rule is to uniformly and gradually change the position of the well in order to avoid tearing off and shifting soil masses near the lowered section. The probability of tilting is then the slightest. Alignment of the well is also easier when the external trench on the side of the well on which we want it to tilt is excavated in order to bring it to a vertical position (Fig. 8). In this case, on the opposite side, the acting soil pressure is increased by making an embankment.

SUMMARY

Wells are specific structures, implemented in stages, and their static analysis must take this stepwise approach into account. This applies in particular to the soil pressure distribution that changes in the successive stages. Sunk wells are monolithic systems characterised by both spatial static work and changes in static diagrams during their implementation (Figs 9, 10, 11 and 12). In the first phase of lowering, the well is a cross-section with its upper and lower edges free. After lowering to the planned depth and after making a bottom plug, its lower edge is supported on the plug's perimeter. Not accepting the spatial nature of these structures in calculations results in significant inaccuracies in the values of calculated internal forces. As regards modelling with 3D software, it is necessary to take into account their phased implementation.

When constructing sunk wells, it is worth remembering about the possibility of using an anchor ring, which can partially take over the buoyancy force acting on the structure after making the bottom plug and pumping out the water from inside. The solution with the anchor ring enables to design and lower a light steining segment embedded in a thixotropic suspension, which is of particular importance for economic reasons. Consequently, this saves approx. 40–60% of the weight of concrete that would be needed as a ballast to ensure sinkability and buoyancy stability for a traditional well, without an anchor ring.

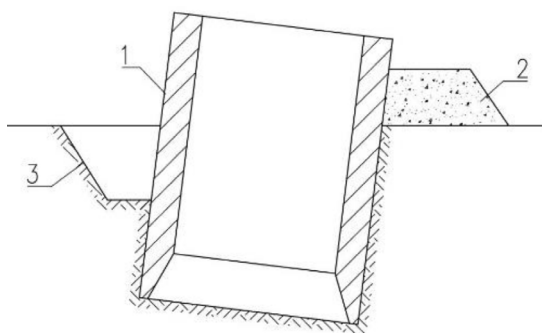


Fig. 8. Alignment of the tilted well: 1 – steining, 2 – weighting embankment, 3 – trench facilitating alignment (Szymczak-Graczyk, 2021)



Fig. 9. Construction works on sinking the well in Bydgoszcz (the author's photo)



Fig. 10. Construction works on sinking the well in Konin (the author's photo)



Fig. 11. Construction works on sinking the well in Suchy Las (the author's photo)



Fig. 12. Construction works on sinking the well in Sobota (the author's photo)

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WYBRANE ZAGADNIENIA DOTYCZĄCE PROJEKTOWANIA I WYKONYWANIA ŻELBETOWYCH STUDNI OPUSZCZANYCH

STRESZCZENIE

W artykule podano podstawowe informacje dotyczące projektowania i wykonywania studni opuszczanych. Studnie są obiektami inżynierskimi powszechnie stosowanymi w budownictwie szczególnie w trudnych warunkach gruntowych lub na niewielkiej powierzchni placu budowy. Wykonywanie studni odbywa się metodą „tnij i opuszczaj”, co oznacza, że pierwszy opuszczany segment zaopatrzony jest w nóż, który rozcina grunt, a konstrukcja studni zagłębia się w nim. Podczas projektowania należy uwzględnić etapowość wykonywania konstrukcji oraz ich przestrzenną pracę. W artykule podano obciążenia występujące podczas realizacji i eksploatacji studni opuszczanych oraz założenia i wytyczne do wykonywania obliczeń statycznych i wymiarowania studni. Przy znacznej wysokości płaszcza studni (przy dużych głębokościach studni) najczęściej wykonuje się betonowanie i opuszczanie w dwóch lub trzech segmentach. W pracy podano przebieg wykonywania studni, zmieniające się schematy statyczne oraz sposób uwzględnienia ich w obliczeniach. Omówiono metodę opuszczania studni wraz z możliwymi trudnościami wykonawczymi. Artykuł uzupełniono o przykładowe rysunki zbrojenia płaszcza, noża i płyty dennej studni. Zamieszczono fotografie wybranych realizacji studni opuszczanych.

Słowa kluczowe: studnie opuszczane, zbiornik cylindryczny, zbiornik prostopadłościenny, nóż studni, korek betonowy, pogrążalność studni