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Research paper

An application of reinforced concrete vaulted slabs and rafts in deep excavation works

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Abstract: The overall efficiency of a construction of a deep excavation urban project does not depend only on the duration of the construction but also on its influence on the urban environment and the traffic [9, 10]. These two things depend greatly on the excavation method and the construction stages defined during the design process. This paper describes the construction stages of three metro stations (two stations in Warsaw and one in Paris) and discusses their advantages and disadvantages including among other things its impact on neighbouring infrastructure and the city's traffic. An important conclusion drawn from this analysis is that the shape of the slabs used can considerably affect the design and the construction stages. For example, a vaulted top slab allows an almost immediate traffic restoration and a vaulted bottom raft allows a much shorter dewatering period.

Keywords: metro station construction, urban construction, construction stages, soil-structure interaction, diaphragm wall, vaulted slab, deep excavation

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1. Introduction

The city of Warsaw is currently profiting from two subway lines [4]. First, south-north direction, which was built during the times, when due to geopolitical changes the “deep” subway concept was enforced, earlier pushed as a shelter for the time of war. The second line, east-west direction, passing underneath the Vistula river and is still under construction.

In opposition, the city of Paris has started the largest infrastructure project currently constructed in Europe: The Grand Paris Express, with 68 newly built metro stations and 200 km of tunnels, some of which will be open for the Olympic Games in 2024. Such a large number of underground structures with similar excavation depths and geometry (the metro trains and therefore the platforms have always the same length) need a perfectly optimised design.

The article is a development of [1], where the author described the construction stages of the underground stations completed in Warsaw in the early 2000s. One of the conclusions of [1] was that the construction of vaulted foundation rafts instead of flat regular foundations rafts were more efficient due to the stress distribution: compression in the vault requires less steel and concrete than bending.

Today, in 2020, about fifteen years later, such vaulted foundation rafts were applied for the construction of the Southern Section of Line 15 of the Grand Paris Express.

2. Experience

Although the mentioned metro lines have been engineered in entirely different conditions of access to knowledge and technology, in all cases the structure interacts with the subsoil, which makes it a valuable experience.

In tunneling, it is the soil-structure interaction that results in efficient construction works and a lack of interference of the city traffic [1].

On the other hand, there is the construction of metro stations. Contractors executing the works on the area bordered by diaphragm walls got used to the fact that the area will be occupied by the structure in the future, so they delay the backfilling of the top slab and the delivery of the area to the city. Why? Because no specific deadline was set in the tender requirements for restoring traffic.

The shape of the top slab will influence the possibility of reestablishing the traffic on the ground, as it needs to resist the weight of the backfill and the traffic without temporary columns. An efficient way for such a design is to change its geometry from a flat slab to a vaulted slab where the compression forces resulting from the backfill weight will be transferred on to the diaphragm walls and then on to the subsoil that is surrounding the station.

Such interaction of the retaining walls with the soil is not used in the urban building industry, and therefore the structural designers of the stations are used to flat slabs supported by columns and walls [9, 10].

As a result, metro stations are built with columns transferring the load on the foundation slab to equalize the uplift of the groundwater. The dewatering process reduces the water pressure under the foundation raft during the construction works. For a flat raft, the dewatering must continue until the weight of the interior of the station supersedes the initial water pressure. Usually, this happens only after the backfilling of the top slab as the structural elements of the station are thin and light.

Let us consider a solution where instead of a flat foundation raft and top slab, a vaulted raft and top slab are applied respectively. Such a design would imply that the intermediate slabs can be held on thin columns transferring only their loads, not the loads of the top slab and the backfill, nor the water pressure.

Where does the difference in design and execution of tunnel linings and metro stations come from? They are both designed by specialists from various branches of the construction industry. For example in mining, the shafts have circular cross-sections with flexible primary linings [5] that encourages deformation of the surrounding soil and therefore decreasing its pressure.

All of the ventilation shafts of the Warsaw subway have a thick frame casing, with a rectangular cross-section [6]. Its capacity to withstand the soil and water pressure comes off its walls' thickness and quantity of reinforcement, not its shape. A circular shaft covering the same cross-section area, could be constructed with much thinner walls as only there would be little bending and mainly compression stresses (so called hoop stresses) within the cross-section. Let's take an example that goes back in history –farmers built circular wells, not rectangular ones. The same procedure is followed by designers of tunnel linings, but not by the designers of metro stations. The shape of the station is usually imposed by architects and engineers only check the structural load-carrying capacity of each element, not being able to influence the overall construction concept.

3. Ratusz station

The Ratusz Subway Station, completed in 2001 with external dimensions 157 × 22 m, is retained by 18 m deep, 0.8 m thick diaphragm walls. Until the final excavation depth was reached, the walls were supported at two levels – the top slab and the intermediate slab, then the foundation raft was poured. The surface above the station was excluded from use for the time of the construction works. Temporary columns were supporting the slabs and placed into 5-meter-long barrettes [1]. The detailed construction stages of the Ratusz station are illustrated in Figure 1.

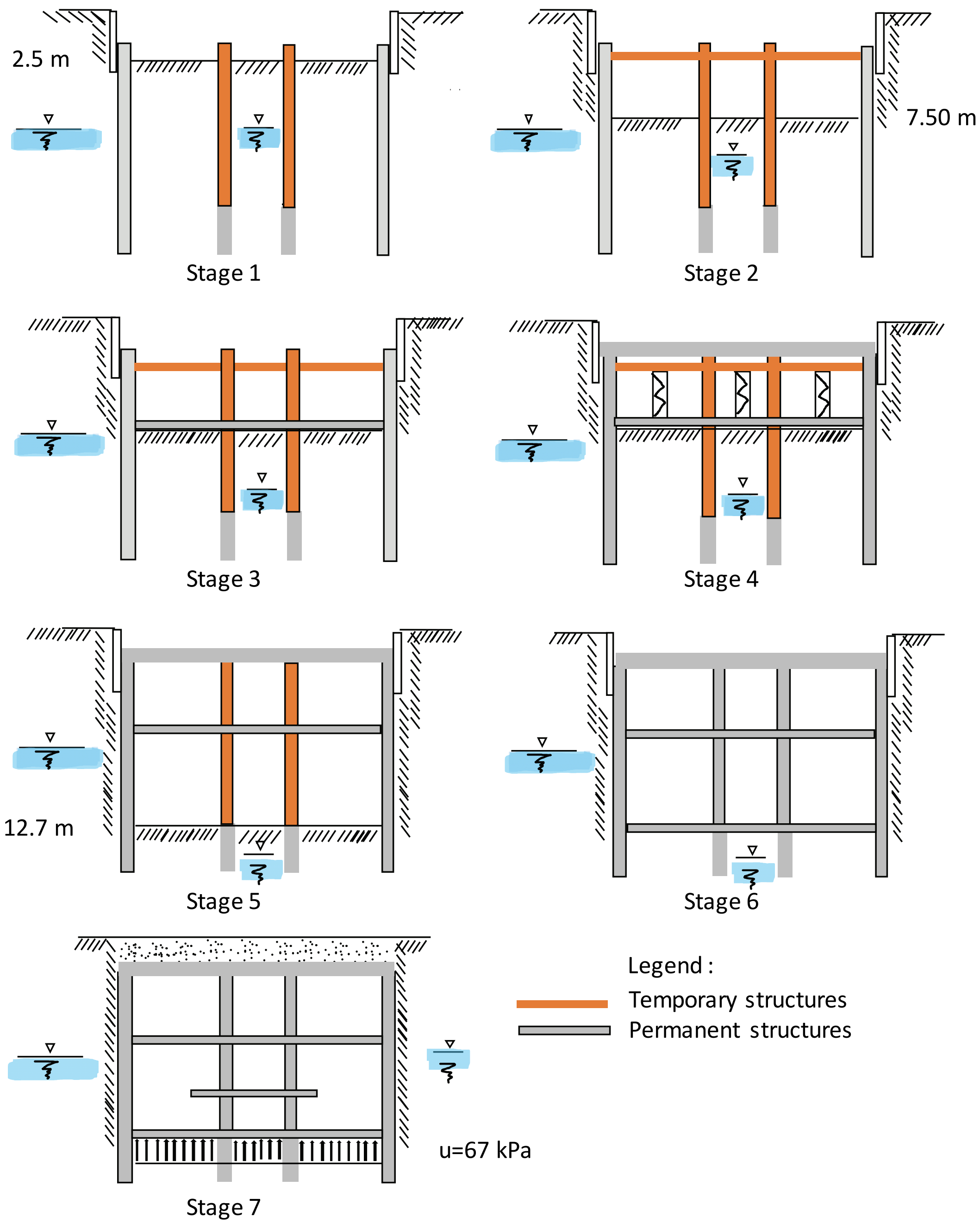

Fig. 1. Construction stages of Ratusz Station

The first two constructions stages do not need any further explanation as it is a classic bottom up sequence with one level of strutting. When the designed 7.5 m depth was reached, the intermediate slab was reinforced and concreted on the levelled subsoil. After the setting time of the intermediate slab's concrete, scaffoldings and formworks were placed in order to complete the top slab. Once again, after the setting time of the top slab's concrete the construction sequence could continue and the soil from underneath the intermediate slab was removed to reach the final excavation level – 12.7 m. The groundwater level was 6 m below the terrain level – right below the intermediate slab, so the works below the intermediate slab were preceded by dewatering another 6 meters, up to 1 m below the bottom of the foundation raft [1].

4. Marymont station

Marymont Subway Station's external dimensions are 156 × 18.4 m. The depth as well as the thickness of the diaphragm walls are the same as those of Ratusz Station.

The construction stages of Marymont Station are shown in Figure 2. The construction has started in 2005 and continued during winter. Thanks to the construction of the upper slab, it was possible to proceed with further works in a covered, closed "hall" where the concrete technological processes were independent of the very low temperatures which occurred during that winter.

At the serviceability state, the walls are propped by two slabs (an upper and an intermediate slab) and a foundation raft. During the construction of the Marymont Station, barrettes were not concreted nor temporary columns were inserted. The intermediate slab, too weak to transfer the self-weight exclusively on the diaphragm walls, was suspended on steel tendons – Macalloy rods, to the thicker, upper slab. Schemes of the designed suspenders and photographs from the construction site are illustrated in Figure 3 and Figure 4.

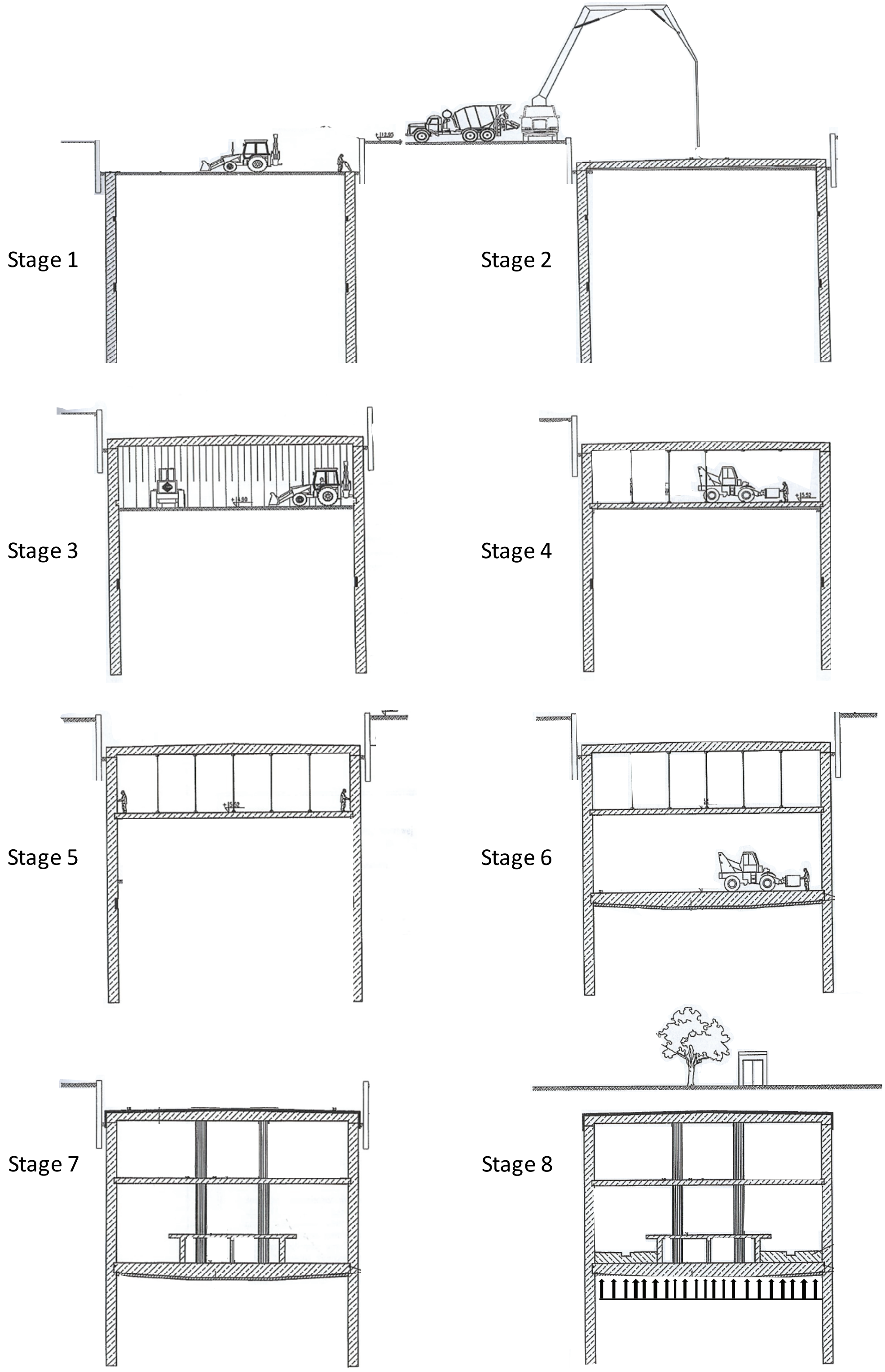

Fig. 2. Construction stages of Marymont station [1]

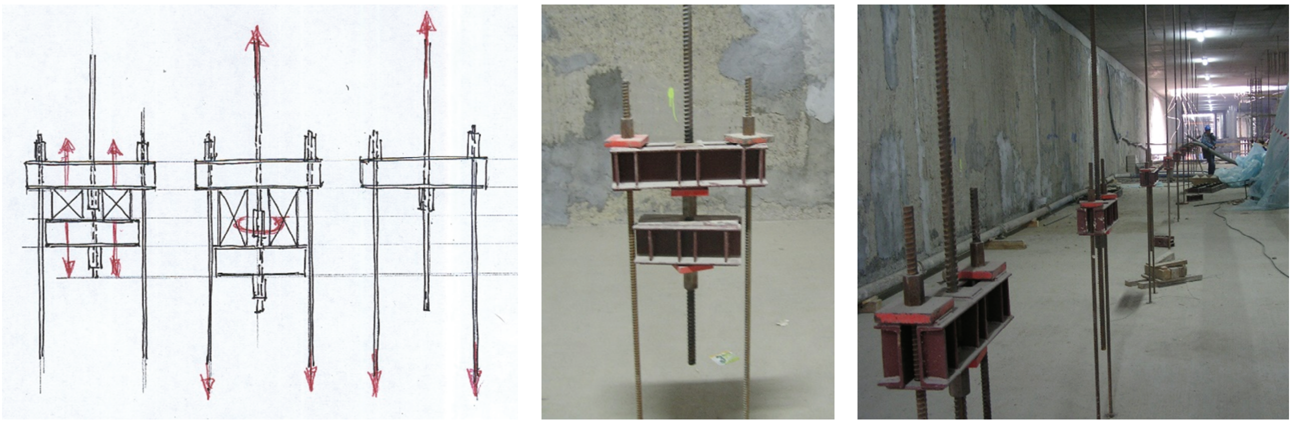

Fig. 3 Tensioned rods holding the intermediate slab [1]

Fig. 4. The column reinforcement, concreted through an opening in the slab [1]

5. Les Ardoines

Les Ardoines Station's external dimensions are 111 × 31.2 m [2]. The mechanical toe (required for the wall to keep the horizontal equilibrium) and the hydraulic toe (required the wall to reach the impermeable soil layer) of the diaphragm wall are 39 m and 48 m below the natural ground level respectively. Les Ardoines Station was constructed by the classical bottom-up method. Figure 5 shows the cross-section of the station when the final excavation depth was reached. As illustrated, there are three temporary steel strut levels with four excavation levels (three under the steel strut and the final excavation level).

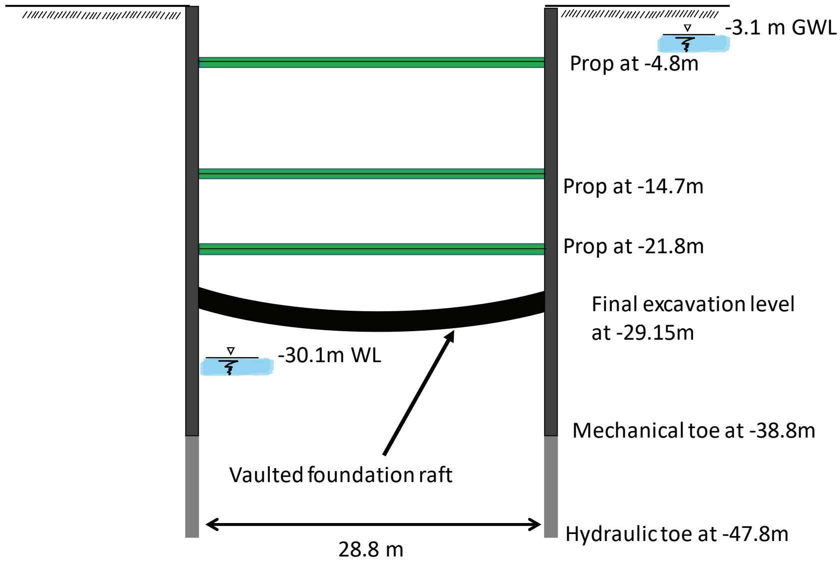

Fig. 5. Les Ardoines cross-section [3]

In order to have less tasks to deal with on site, the interior water level has been pumped at once, directly to –30.1 m. The flow rate pumped by the water pumps inserted below the final excavation level was kept at circa 6 m^3/h during a 10-month period, from the first excavation level (at –5.4 m to install the first level of props) to concreting of the vaulted foundation raft [3]. After the setting time of the vaulted slab's concrete, the dewatering has been intercepted. In order to verify and measure the compressive stresses in the vaulted foundation raft, strain gauges were welded on its upper and lower layers of steel rebars. Figure 6 illustrates the position of the strain gauges installed in the raft and Figure 7 shows the strain gauges measurements.

According to the pumping test performed on the Western pit just after the finalisation of the diaphragm walls, but before any excavation, the majority (10 m) of the water pressure inside the pit comes back in the first 2 hours after ceasing the pumping. Then, in the next 48 hours the pressure increases less rapidly of about 4 m. The pressure didn't come back to its original level in the first few weeks and remained stagnant at about –14 m. This information is important as the compression in the vaulted slab should increase accordingly.

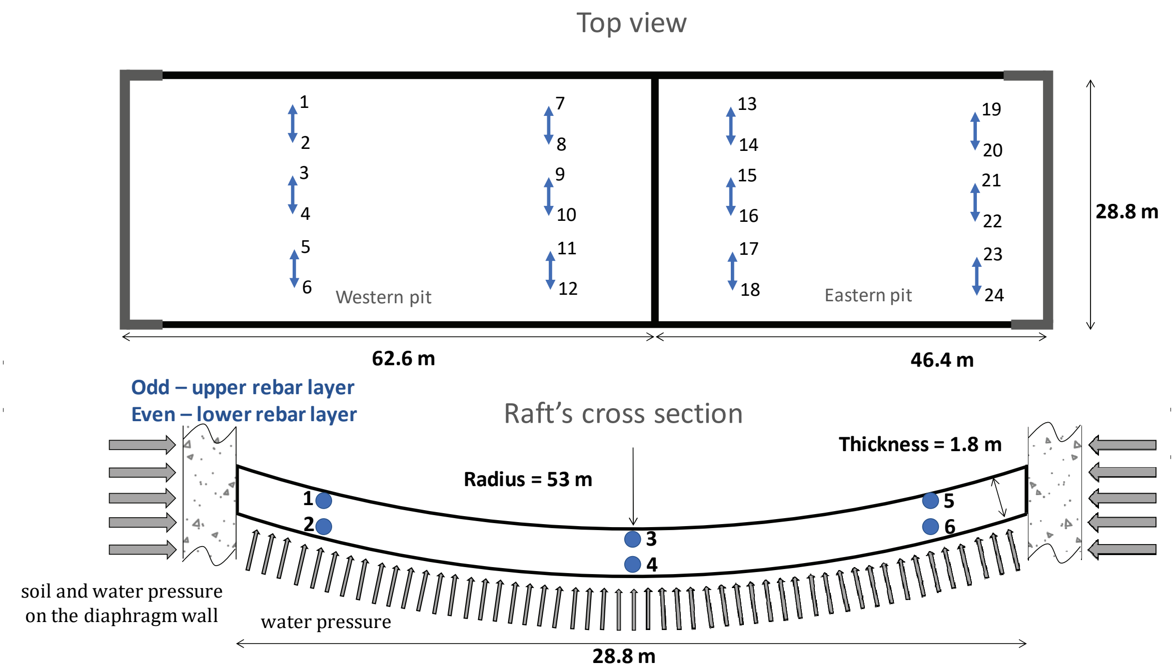

Fig. 6. Strain gauges installed in the Les Ardoines vaulted raft with a scheme of applied pressures

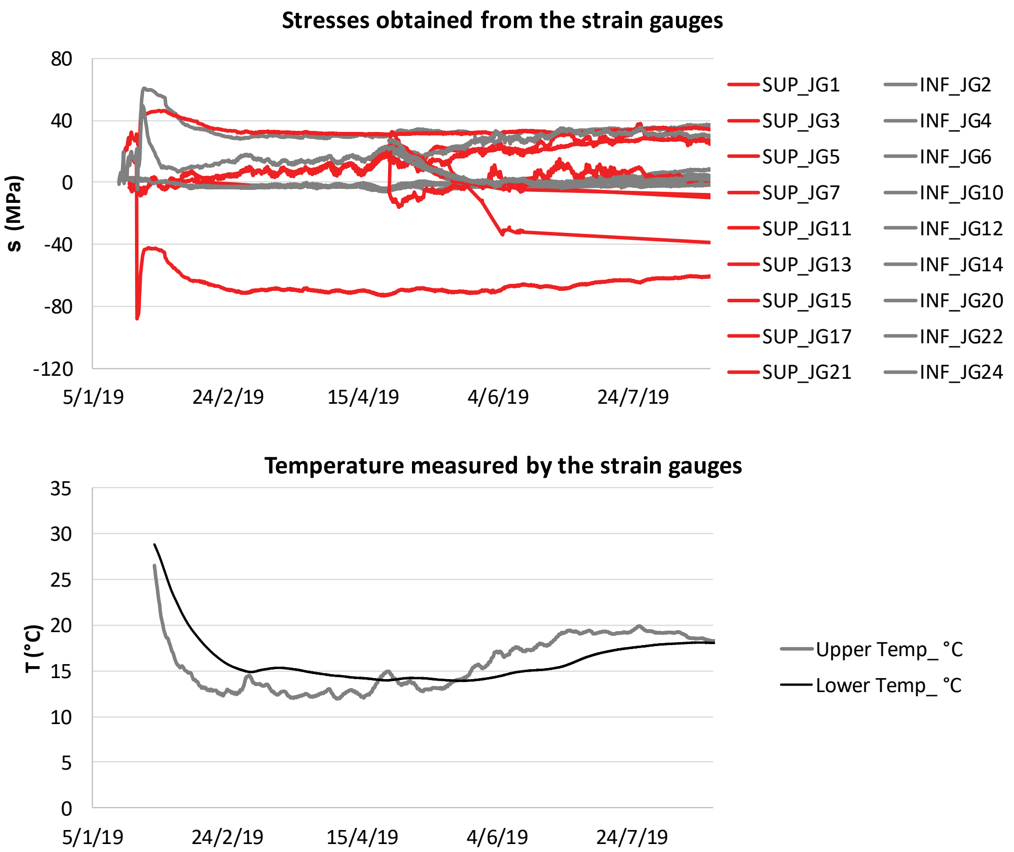

Fig. 7. Strain gauges results (**s** positive – compressive hoop stress)

The measurements show the compressive stresses in the vaulted slab and the temperature variations. The results are lower than predicted which is partially due to the fact, that the water pressure didn't come back to its initial level immediately (as showed the pumping test). The temperature measurements show a decrease during the setting of the raft's concrete.

6. Discussion

This part of the paper is a discussion of the advantages and disadvantages of the structural key elements of each of the stations.

6.1. Upper slab of the station

All seven stations of the second subway line in Warsaw were constructed by the top-down method [8]. After securing the slopes of the future excavation, removing the underground services and excavating until the upper slab level and concreting it, further works were conducted under the cover of this upper slab. Consequently, there should be no obstacles to restore the city's traffic after hardening of the upper slab's concrete, laying the insulation and backfilling. This is a crucial advantage of the top down method – a significant time reduction of traffic disruption.

For none of the Warsaw's metro stations, the contractors decided to restore the traffic and continue the excavation works underneath the upper slab. In the case of those structures, it would imply the necessity of strengthening the upper slab or supporting the diaphragm walls in the first period of the construction.

It is not easy to evaluate the costs emerging from several years of traffic disruptions in the city centre and compare them to the costs of reinforcement and supporting the upper slab that would be required to restore the traffic on the ground level. However, if we consider the upper slab's shape to be a vault and not a simple flat slab, it would be needless to support the upper slab and possible to re-establish the traffic on the surface as soon as the upper slab's concrete has hardened.

It may be, that in some cases the upper slab's vault of the station should be placed lower when the dead loads of the backfill above the vault will be larger than loads of vehicles the force compressing the soil remains in its core and the strut's load of the vault is transferred on the diaphragm walls below.

An additional advantage of the vaulted upper slab would be the durability of the structure and the fact that fewer materials (less reinforcement as a bent cross section requires more steel than the compressed one) would be used. A compressed vault, spanned between the diaphragm walls of the station would be thinner than a flat, bent slab supported at its ends by the diaphragm walls and by walls or columns in the central part of the station. There would be less cracking, less reinforcement, and the slab would accumulate “an extra stock” of load carrying capacity for future unknown loads. Another advantage would be the possibility to leave the underground services in the subsoil, only by suspending them until the backfilling of the upper slab is made.

In order to encourage the contractors to organize the building works in that way, in the tender conditions, a period of exemption of fees for the occupation of streets should be set. In the case of exceeding this period, additional fees would apply to the contractor.

6.2. Groundwater pressure – reverse vault

Metro stations in Warsaw, are located below the groundwater level and are subjected to uplift [7], and so is the Les Ardoines metro station in Paris (Fig. 5). Even if the diaphragm walls were deep enough to reach an impermeable soil layer, and/or there was a jet-grouting injected plug, the heterogeneity of the soil layers and possible leakages between the diaphragm wall’s sections will not guarantee the long-term disappearance of the water pressure. With time, water will rebuild its pressure to its initial level and will displace the station. For the metro stations built in Warsaw, the stability of the excavations and the foundation raft will be maintained provided that the groundwater level will not be restored before the backfilling of the top slab. This implies that the dewatering system must be functioning until the finish of the works and significantly influences the construction costs.

At les Ardoines, the dewatering time (and therefore its cost) was greatly reduced as it was stopped when the raft’s concrete has hardened. In terms of water pressure, most of it appeared a couple of hours after the interception of water pumps. The strain gauges installed on the rebars of the vaulted raft show compressive (hoop) stresses as the design predicted. On the other hand, for the diaphragm walls, the large compressive stresses in the vaulted raft will cause an increase of the bending moments in the walls which need to be taken into account in the design. Another element that is worth mentioning is the fact that the dewatering under the final excavation level increases the passive pressure to its maximum potential as the effective stress is equal to the total stress. However, when the pumps cease to work, the water pressure is applied vertically (on the raft which applies the compressive stress) and horizontally. The horizontal water pressure with a trapezoidal distribution will decrease the available passive strength.

The displacements will decrease even more if the vault was linked with the diaphragm walls with the stiff joint.

Figure 8 shows the scheme of working the metro station structure with soil-structure-water interactions; a) the straight foundation slab and b) the proposed solution in the form of the vaulted foundation slab.

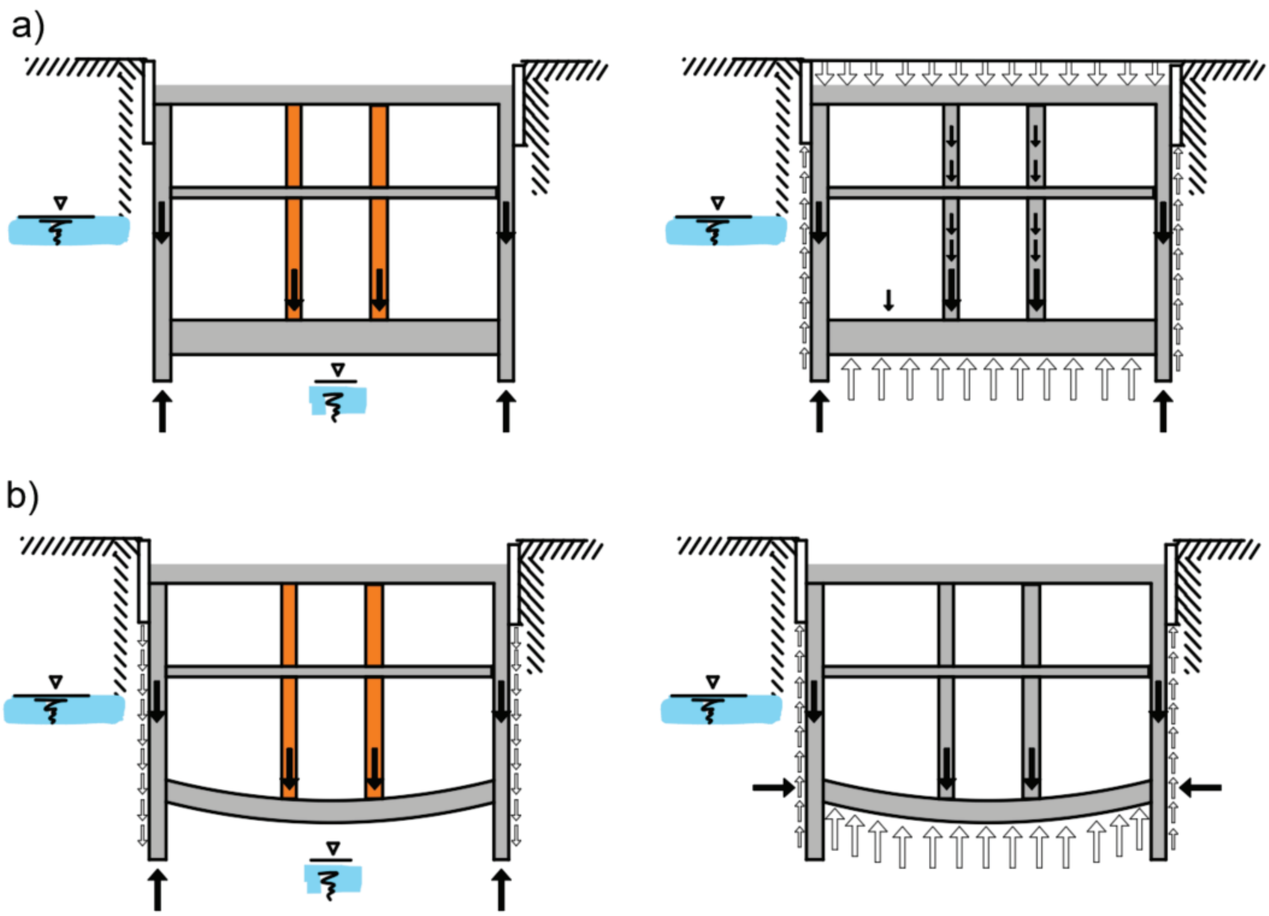

Fig. 8. The working diagrams of the subway station structure with soil-structure-water interactions; a) the straight foundation slab, b) the proposed vaulted foundation slab solution

6.3. Advantage and disadvantage of each of the stations

Table 1 outlines the advantages and disadvantages of each of the design and construction technologies of both Warsaw metro stations (Ratusz and Marymont) and the Parisian metro station (Les Ardoines) based on gained experience.

Table 1. Advantages and disadvantages of the described technologies of the subway construction

	Advantages	Disadvantages
Ratusz Station (Warsaw)	• Construction works can be carried on with no disturbance by the usage of the area above the station's slab. • The possibility of conducting works during winter, below the top slab roofing	• The necessity of constructing barrettes and temporary columns • The necessity of installation of temporary steel struts on the top of the wall • Dewatering during the entire period of construction • The water pressure exceeds the weight of the foundation raft, both slabs and the backfill over the station • Handing over the area above the station only after finishing the construction of the station
Marymont Station (Warsaw)	• Efficient in carrying on the construction works, lack of disturbance by the usage of the area above the station plate Construction works can be carried on with on disturbance by the usage of the area above the station's slab • The possibility of conducting works during winter, below the top slab roofing • The space without temporary columns allows for easy manoeuvring and a faster excavation process	• The need to strengthen the top slab to transfer the load of the suspended intermediate slab. • The water pressure possibly exceeds the weight of the foundation raft, both slabs and the backfill over the station • The surface above the station was excluded from use for the time of the construction works
Les Ardoines (Grand Paris Express)	• The final excavation level was reached in just six months • Water pumps were stopped when the vaulted raft was concreted • Thanks to the vaulted raft, no barrettes, piles were needed under the raft	• The installation of three levels of temporary steel props • The surface above the station was excluded from use for the time of the construction works • The water pressure applied on the vaulted raft implies larger bending moments in the diaphragm walls at the level of the raft

7. Conclusions

Based on structural design and in-situ experience from all three stations the following conclusions can be drawn and directions pointed for future constructions of metro stations.

The advantages of a vaulted top slab are:

- Immediate traffic restoration.
- Less reinforcement in the top slab as compression stresses require less steel than bending stresses.
- Absence of temporary columns between the top slab and the intermediate slab.

The advantages of a vaulted foundation raft are:

- A shorter dewatering period as the water pressure can be equilibrated by the compression in the raft and therefore the weight of the diaphragm walls.
- Less reinforcement in the raft as compression stresses will require less steel than bending stresses.
- Small displacement of the vaulted raft resulting from the compression (significantly lower than due to bending of the bottom raft).

There is one more essential advantage of underground structures loaded by soil – the possibility of taking into account the soil-structure interaction. Naturally, the lining should be much less rigid than the discharging vaults created in the soil. This seems to be the right direction in the designing of genuine underground constructions. The supplies of the load-carrying capacity of such structures become enormous. It can be stated, that this is the reason why old, vaulted tunnels serve to this day, while recent, tunnels with rectangular cross sections undergo cracking. An underground structure with a bearing system in the shape of a frame, can only carry the amount of weight that is transferred to its most stressed, bent cross-section. When exceeding this weight, the destruction of the structure will begin.

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Zastosowanie żelbetowych płyt sklepionych podczas wykonywania głębokich wykopów

Słowa kluczowe: budowa stacji metra, budownictwo miejskie, fazowanie robót, interakcja konstrukcji z gruntem, ściana szczelinowa, płyta sklepiona, głęboki wykop

Streszczenie:

Ogólna efektywność budowy miejskiej inwestycji głębokiego wykopu nie zależy tylko od czasu trwania budowy, ale także od jej wpływu na środowisko miejskie i ruch drogowy [9, 10]. Te dwie rzeczy zależą w dużej mierze od metody wykopów i etapów budowy określonych w procesie projektowania. W niniejszym opracowaniu opisano etapy budowy trzech stacji metra (dwóch w Warszawie i jednej w Paryżu) oraz omówiono ich zalety i wady, w tym m.in. wpływ na sąsiadującą infrastrukturę i ruch w mieście. Ważnym wnioskiem wynikającym z tej analizy jest to, że kształt zastosowanych płyt może mieć istotny wpływ na projekt i etapy budowy. Na przykład, górna płyta sklepiona pozwala na niemal natychmiastowe przywrócenie ruchu, a dolna płyta sklepiona pozwala na znacznie krótszy okres odwadniania. W rezultacie powstała bardziej globalna dyskusja na temat interakcji konstrukcji z gruntem, gdzie wykorzystywane są sklepione elementy konstrukcyjne. Gdy nacisk gruntu jest wywierany na sklepione górną płytę lub płytę denną, tworzenie się sił obręczowych w betonowych przekrojach poprzecznych pozwala na dodatkowe przenoszenie obciążeń i tym samym oferuje znaczne korzyści i szerokie możliwości projektowe.

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