CONSTRUCTION OF METRO LINE 4 IN BUDAPEST

GENERAL DESIGN OF KELENFÖLD METRO STATION

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Design and construction of Kelenföld metro station was a real challenge for all participants: for designers and contractors alike. Working on an operational railway station demanded stern procedural and technological discipline. Application of the Milanese method made it possible to disturb the surface facilities only temporarily, and to organise the finishing works outside of the railway territories in operation. Application of these technologies in Hungary was quite unknown before this project, it provided the participants valuable experiences.

Keywords: *metro, civil engineering, railway bridge, underpass, D-wall, tunnel*

1. LOCATION

Kelenföld Station of Budapest Metro Line 4 is constructed under 28 tracks of Kelenföld railway station. Besides serving as an underground – railway junction, the station is connecting Kelenföld and Őrmező urban districts as a pedestrian underpass as well; forming a hub with the existing and under construction transport lines. Design and construction of the structure was heavily influenced by the operational railway station, safe operating of which had to be maintained throughout the works.

2. ANTECEDENTS

Permission design as well as the tender drawings were prepared by Főmterv Zrt. based on the architectural guidelines by Palatium Stúdió. The FIDIC yellow book tender called on the basis of these drawings was awarded to Hídépítő Ltd. in 2007. General constructional design was made by Speciálterv Ltd. on the awarded company's commission. The assignment contained

Fig. 2: General cross-section beneath the railway bridge

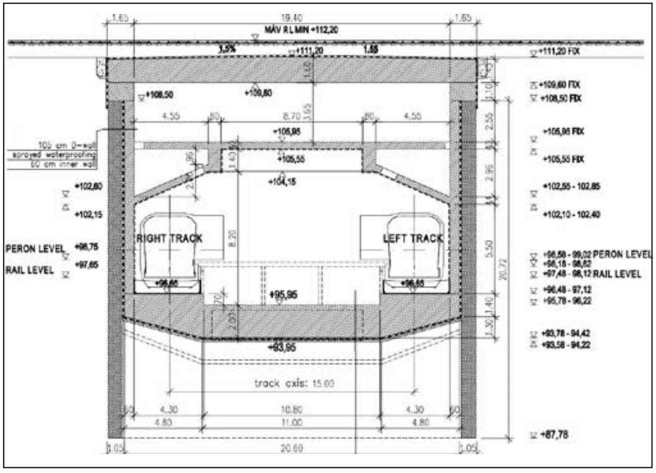
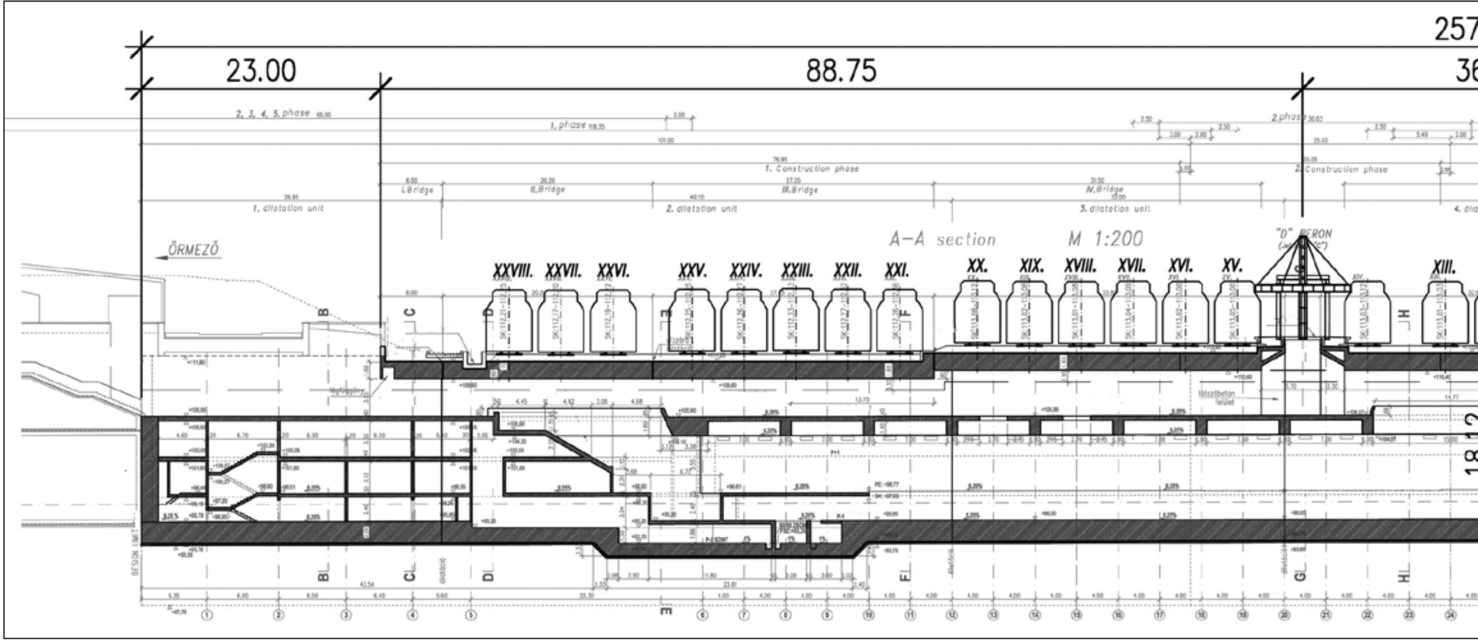


Fig. 1: Longitudinal section of the station



the structural design of the load-bearing structures of the station as well as the design to transform the railway station in order to adopt it for the works. Based on the permission design and the tender drawings the structure beneath the railway was constructed by the Milanese method, which means, that after completion of the top slabs the surface – the railway tracks in this case - can be reset, while excavation and further construction of the shaft is carried on beneath the top slabs.

3. GENERAL EXPOSITION, CONSTRUCTION

On the Etele tér side the structure under the railway station is connected to the previously constructed TBM launching shaft. The pedestrian underpass and station shaft is 260 m long; making it 340 m together with the adjoining train reversing structure on the Őrmező side. A 90 m long SCL (Shotcrete Lining) tunnel is connencted to the D-walled train reversing structure, so the entire length of the designed civil engineering section is 430 m; which means, that Kelenföld Station is the longest station in Underground Line 4. (*Fig. 1)*.

1.00 m thick and 22-23 m deep parallel D-walls were lowered at the section of the shaft located beneath the rails, distance between their axis is 21.60 m. The top slab, which is a ballasted railway bridge by function, is connected to the capping beam of the D-walls by flexible joints (*Fig.* 2*)*.

Waterproofing, dewatering system, ballast and railway tracks were constructed on the upper surface of the top slab. Beneath the top slab excavation was carried out between the D-walls while the railway tracks were reinstalled on the surface.

Excavation between the D-walls was done in one go down to the lower level of the base slab, which is approximately 18 m below surface. During this temporary construction stage, in order to avoid the D-walls to be exposed to water pressure the occasional waters found in the cohesive, watertight soil were „let in" by temporarily piercing the panels. The base slab joins the D-wall by moment bearing connection. The force transmitting connection was carried out by applying „Lenton" couplers (*Fig. 3)*. „Lenton" couplers are bolted reinforcement bars used for splicing. The ordinary reinforcement steel bars are lathe-turned to a coned shape, onto which the splicer shuck is bolted. The shucks – prepared in advance in the reinforcement

Fig. 3: Coupler connection joint of D-wall and base-slab

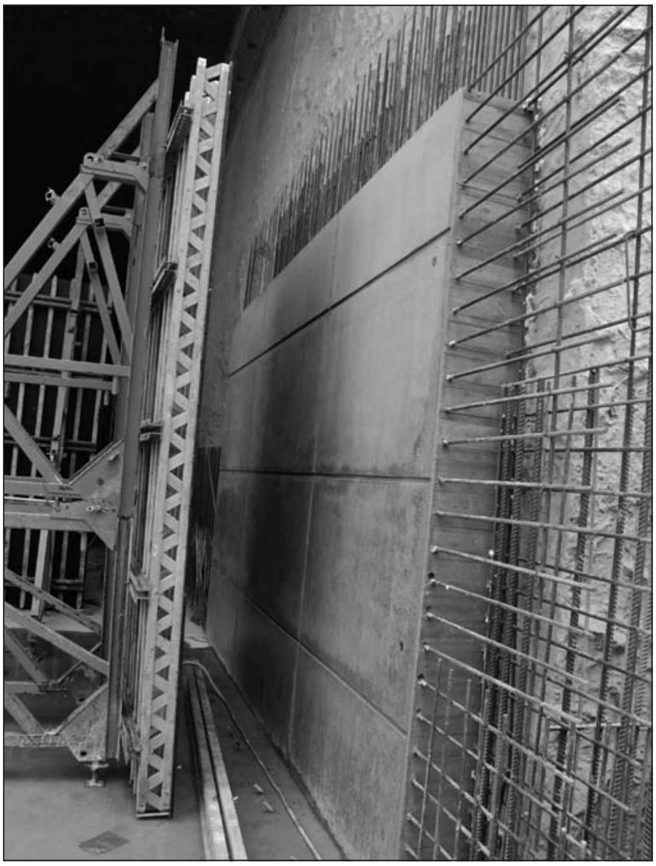
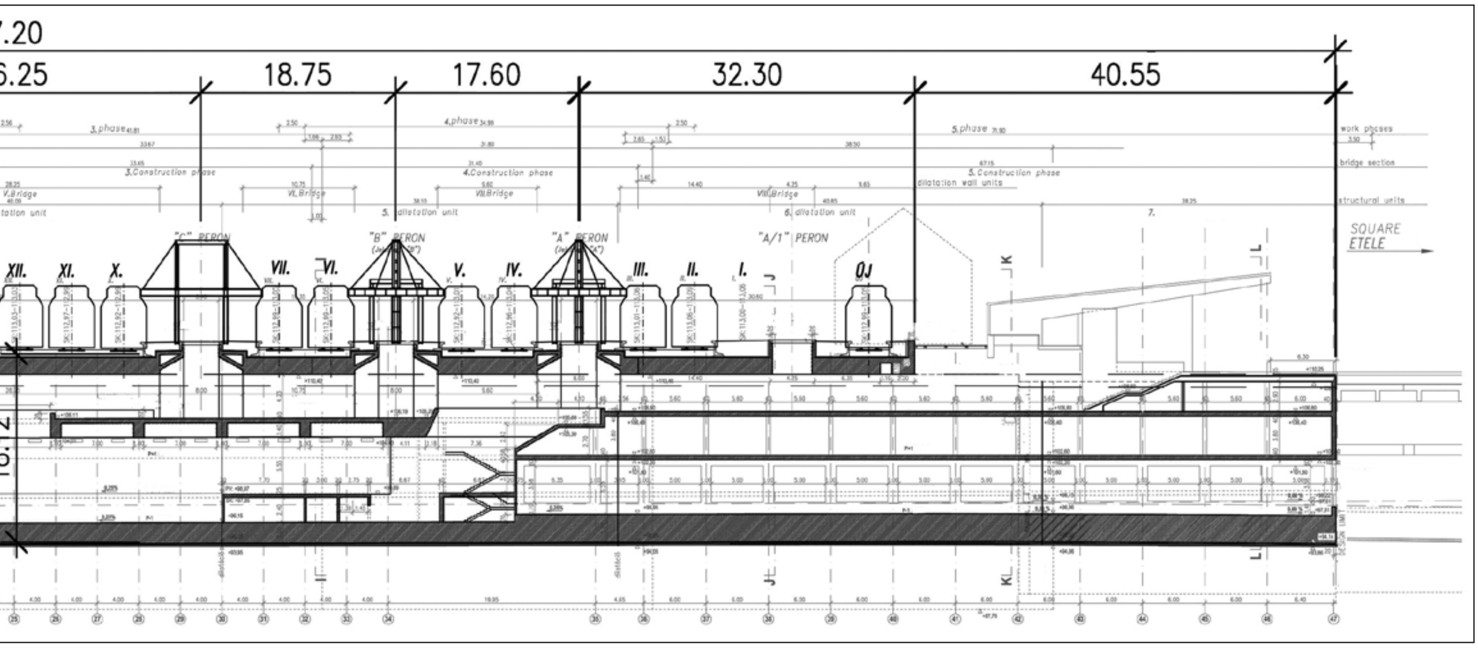


Fig. 4: Construction of visible concrete surface structure



of the diaphragm wall and protected by temporary plastic caps – are to be found on the diaphragm wall surface already stripped, and the force conducting steel reinforcement will be joined into these.

Installation of the reinforcement and shutters of inner walls took place following casting the base slab. A significant proportion of these walls are visible concrete surfaces, for the fine implementation of which the application of specially surfaced formworks, special concreting technology and stern procedural discipline are necessary (*Fig*. 4*)*.

The top slab at most parts of the shaft under the station's platforms is supported by a frame structure (*Fig*. 5*)*.

Connection between the upper pedestrian underpass level and the platforms between the undergruond rails is provided by elevators, stairways and escalators. Concurrently to the underground shaft construction, the surface platform roofs were also transformed. Owing to minimalization of the construction program durations, the new roofs segments harmonizing with the forms of the existing platform roofs are applied.

The shaft construction works crossed the entire service system of the station on the sides of the tracks; therefore, appropriate substitution and diversion in different construction phases had to be designed for the entire overhead cable network, signals and security system elements. Conditions of safe operation had to be maintained for each phase of the works, design for each phase had to be prepared.

Construction works crossing the station were carried out in five main construction phases. D-walling and reinforced concrete structure construction works had to be organized on the „islands" bordered by operating railway tracks. Construction works amid tracks raised severe technological problems. High voltage cables running alongside the site area made the craneage, D-walling and servicing activities even more difficult. Concrete is supplied through the existing pedestrian underpass, restricting the passenger area, applying concreting tubes. Materials were transported on railway in and out of site using the tracks being reinstated.

Fig. 5: Frame section of the inner slab after removal of shutter

Fig. 6: Completed primary lining of SCL tunnel

The train reversing structure joining in to the shaft on the Őrmező side consists of two structural units: an 80 m long reinforced concrete structure built between diaphragm walls and a 90 m long SCL tunnel. The reinforced concrete structure, similarly to the section under the railway, is constructed by Milanese method, however, in this case, not the roof slab but an intermediate slab directly above the clearance envelope of the underground provides the supporting functions. The SCL tunnel, which temporarily functions as a terminal, receives underground vehicles of the station in a unified cross-section. For further perspectives, the metro line can be extended through this tunnel in the direction of Budaörs (*Fig*. 6*)*.

4. STRUCTURAL ELEMENTS, METHODS OF ANALYSIS

4.1 Diaphragm walls (D-walls)

In the area affected by the underground construction middle Oligocene Kiscell clay can be found under the made ground layer. Calculations for the permanent structural state of the diaphragm walls were carried out considering surface loads, at-rest soil pressure and water pressure on the whole surface of the side walls, while for calculations of temporary state, groundwater was only taken into account in the upper weathered medium and fat clay and less weathered medium and fat clay layers. Considering the deeper intact medium and fat clay as watertight, water pressure during construction was not taken into account in this layer; which made it possible to excavate from below the top slab down to the lower level of the base slab (close to 16 m) in one go.

To make sure that this condition be valid, water-conducting steel tubes were installed in the watertight layer behind the 100 cm thick diaphragm wall, so as to eliminate any incidental water pressure. Two tubes were installed for each reinforcement D-wall segments.

Excavation was carried out under regular control measurement surveys and inclinometer readings.

In permanent stage D-walls are carrying the loads imposed on them jointly with the inner walls and supported by the base slab and internal reinforced concrete structures. The D-walls and inner walls are not connected structurally, which means that they are carrying loads proportionally to their stiffness. Nominal thickness of the watertight D-walls is 60 cm at the adjoining platform stairs, and 100 cm at the pedestrian underpass section.

4.2 Top slab functioning as railway bridge

The roof slab of the underground station is a monolithic reinforced concrete slab which also functions as a railway bridge. Considering its structural system, it bears the weight of the slab and of the railway as a single span bridge with two supports. The thickness of the monolithic reinforced concrete slabs concreted on the ground varies between 1.45 and 1.60 m; the upper surfaces incline towards their supports by 1.5%.

Permission design was prepared initially showing bridges' slabs with welded steel main girders embedded into reinforced

Fig. 7: Installation of the reinforcement of a cast in situ reinforced concrete slab-bridge, formwork for visible surface concrete

Fig. 8: Construction of the „U" shaped eigth slab-bridge supporting three railway tracks

concrete. As first phase of the constructional design, economical comparison analysis were carried out assessing the application of a traditional as well as an improved embedded steel girder structure scheme against the monolithic reinforced concrete slab concept with the thickness proposed in the original design. Economical advantages were considered on the basis of structural calculations prepared for each model.

As an improved embedded steel girder concept we proposed the application of steel beams halved longitudinally along the axis of the web. The method commonly used in Germany improves in great deal the load distributional parameters of the joint between steel and concrete by cutting longitudinally the web of the girders in a specific way.

Compared to the traditional embedded steel girder beam solution, considerable thrift in structural steel appropriation can be achieved with the structure constructed along these lines. On the other hand though in temporary (under construction) stage the structure is less rigid, which implies more dense support propping. We were be able to exploit the benefits of this improved structural scheme by considering the construction of the slabs on ground-supported shuttering system.

At the end these slabs were constructed as simple cast-in-situ reinforced concrete slab-bridges due to enormous method-related complications which arose when lifting the steel girders in place amongst several high voltage cables was considered. Reinforcement of the compact slabs casted on ground-supported shuttering system consists of 40 mm diameter reinforcement bars installed in two layers (*Fig*. 7).

Top slab of the pedestrian subway is articulated with work joints and expansion joints bridged watertightly, in accordance with the constructional phases. The expansion joints created eight structurally independent reinforced concrete slabs, the equivalents of eight separate railway upper-decks lying side by side. The slab bridges lead across two to five tracks each, which makes it 28 in total.

On the platform edge of the slab bridges, cantilevers are made with visible concrete surface. The inner voids of these provide ventilation. According to the architects intention, glass slabs between the slab bridges are to provide natural daylight in the subway.

Slab bridge No. 8 is U-shaped layout. The gap in its middle provides connection between the subway and the new „A1" platform (*Fig*. 8).

4.3 Internally reinforced concrte structures

Between the diaphragm walls and under the roof slab, inner reinforced concrete structures are made. These are: the base slab, the platform level and a slab labelled „P_1" at pedestrian underpass level and mechanical engineering areas.

Thickness of the base slab varies between 1.40 and 2.70 m in cross direction, it's connected to D-walls by moment bearing joints. Applying „Lenton" shucked steel splicers for these joints made it possible to distribute the moment between base-slab and D-wall.

The structure as a whole as well as the base slab on its own, are both calculated for uplift in its permanent state. Considering the fact, that the structure is embedded into a hard, watertight layer of soil, uplift-related forces are foreseen to come in effect years and decades after the construction is completed.

The subway level above the passenger traffic section of the platform level is a beam supported reinforced concrete slab (*Fig*. 9). Its thickness is 40 cm, supported by a 1.80 m high beams at every 7.0 m, which are joined into a 1.80 × 0.80 m longitudinal girder. The inner walls, the angled and the horizontal slabs are forming a frame. At the calculation several aspects had to be taken into account. Forces acting in the structure are massively affected by the horizontal supporting rigidity of the frame, which contains uncertainties for some degree due to the fact, that it's the soil which is supported by the frame on the outside. Calculation for one of the extreme limit states of the structure was made neglecting the soil, while calculation for the other one was done supposing infinitely rigid horizontal support. Reality lays somewhere in between. Signs of moment are opposite for the two extreme limit cases for a considerable section of the slab. Finally, we took into account the elastic support of the soil, and created the graphs of overall moments for the calculation by iterating between the two extreme limit cases. Above the mechanical engineering areas

Fig. 9: Downward cross-supported reinforced concrete roof slab

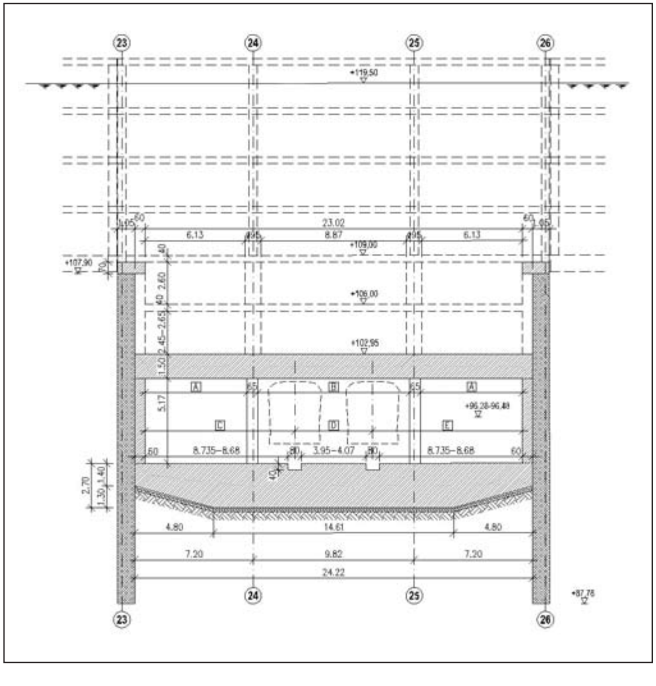
of the structure, top slabs are 40 cm thick cast in situ reinforced concrete plates supported by reinforced concrete pillars.

4.4 Temporary access ramp

The removal and transportation of the approximately 120 000 m^3 spoil from an 18 m depth below surface was made possible by a temporary access ramp built in the south-western corner of the shaft, which joined in to the service road of the railway station. This ramp was constructed with pile wall supporting at the deeper parts in the side of the Őrmező hill, and with stabilized ground slope at shallower parts. There are gaps in the pile walls. The diameter of the applied CFA piles is 80 cm; their length is adapted to the depth of the cutting. The applied reinforcement is correlating with the actual strain. At sections where it was allowed by the depth of the cutting and size of the clearance envelope, the pile walls facing each other were countersupported with steel props. The props were made of HEB 300 steel segments. The laminated beams recline on the reinforced concrete support beams distributing the loads of the beams. (*Fig. 10*).

Fig. 10: Construction of temporary access ramp sheltered by anchored piled walls

Fig. 11: Cross-section of the reversing structure



4.5 Train reversing structure

The train reversing structure on Őrmező side is constituted by two structural units: an 80 m long reinforced concrete structure constructed between D-walls, and a 90 metres long SCL tunnel. The cut renforced concrete shaft was built by Milanese method similarly to the section beneath the railway tracks. The difference between them is that the reversing structure's supporting slab is not the top slab located at surface level, but a 140 cm thick intermediate level slab right above the permanent underground rolling stock clearance envelope. Capping beam was built on top of the D-walls, inner walls were constructed next to the inner surface of the D-walls, the base slab is connected to the D-walls by moment conducting „Lenton" joints.

The intermediate level supporting slab was constructed as a two-legged structure for the first phase, but it was supported by pillars erected from the base slab below for permanent stage (*Fig. 11*).

The SCL tunnel joining the cut and cover reinforced concrete shaft bears a cross-section suitable for two underground vehicles. Bottom line of the SCL technology is that a primary lining is formed for the consecutive excavation phases by placing lattice girders configured by steel reinforcing bars and reinforcement meshes and then covering them with shotcrete. The primary lining acts as a load bearing tunnel walling in temporary stage. The completed primary lining is sealed off by watertight membrane. It's followed by the construction of a loadbearing reinforced concrete secondary lining, which supports the loads in permanent stage.

The entire surface of excavation for the reversing structure's SCL tunnel is 100 m^2. Excavation is carried out with one-side gallery and enlargement. The thickness of the closed circular lining is 0.30 m as well as the thickness of the temporary sidewall (*Fig.* 12). Distance between the tracks in the completed tunnel is 4.75 m.

Fig. 12: Construction of SCL tunnel, second phase excavation is ongoing, while the plum kernel shape internal shotcrete lining of the first phase was not yet torn down.

Concurrently with the tunnel construction, continuous monitoring system was operated. Dislocation of the tunnel linings and of the surface was controlled by survey methods, movements of the adjoining D-walls and of the soil was controlled by inclinometers and extensometers; parameters of the ground- and layer-waters were followed with piezometers.

5. CONCLUSIONS

Complexity and dimensions of the construction of the underground station structure beneath Kelenföld railway station made it a real challenge for all participants. As for the structural designer, the most impressive novelty was the process of design updated to and corrected by the regular measurements on site, which is a fairly common practice in the mining industry, but rarely applied for civil engineering design tasks.

Structural assumptions (such as neglecting the water pressure in hard soil), which made the construction economical, were tested against measurements on site. On the basis of these measurements, design assumptions could be verified and, if necessary, the designs could be amended adding or removing specific temporary supporting structures. This feed-back driven practice helps to design enormous structures with extreme complexity and unforeseeable difficulties in an economical way; and it's adopted throughout the industry.

6. REFERENCES

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CONSTRUCTION OF BUDAPEST METRO LINE 4
Detail design of the „KELENFÖLD” metro station
Gábor Pál

The metro station called “Kelenföld railroad station” is the head point of the 4th metro line of Budapest, it's located beneath the 28 tracks of Kelenföld railway station. After its finalization, as a south-west gate of Budapest it creates an intermodal connection between the metro line and the railway system. The structure under construction is the first in Hungary built underneath a railroad station with a separate level junction. The design and construction of this metro station imposed a serious challenge on the designers and contractors. To work on a railroad station in operation requires very strict technological concentration. Applying the top-down excavation method ensured a restricted disturbance of the surface, finishing works can be carried out with an installation not affecting the railway areas.

Gábor Pál (1970) MSC civil engineer (Budapest Technical University, 1994) 1994-1999 designer (FŐMTERV Co.) 1999 onwards executive of SpeciálTerv Ltd. His scope is to manage the 30 employees organisation of designers, and to control and expertly lead the civil engineering design works of the company. General designer of the underground station Kelenföld, which is part of the DBR 4 metro project. Member of Hungarian Group of ***fib***.