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2018

GEOTECHNICAL CHALLENGES IN KARST

ISRM Specialised Conference / Međunarodna konferencija
8. Savjetovanje Hrvatskog geotehničkog društva
Omiš – Split, Croatia, 11.-13.04.2019.
ISBN 87587655865

Stability of excavations in karst for deep underground stations of Lines 1 and 2 of Riyadh Metro Project

Stabilnost iskopa u krškom terenu za duboke stanice linija 1 i 2 Riyadh metroa

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Abstract

Geology of Riyadh area comprises surficial soils over a sequence of sedimentary rocks, bedded Limestone and Limestone breccia. Construction of deep underground stations was carried out in vertical excavations which required support in soils, completely weathered rock and cavities. The excavations were free standing in highly weathered to fresh rock. The support measures for soils and completely weathered rock included flattening of the excavation, gravity walls, soil nails or anchors and shotcrete and secant pile walls with anchors. Selection of the support measures depended on site constrains and soil or completely weathered rock properties. Cavity types encountered included empty cavities, infilled cavities and karstic systems. Support systems for excavations through cavities depended on cavity type, cavity size and risk profile.

Keywords: karst, Riyadh, Limestone, excavation stability, support of excavation, cavities.

Sažetak

Geologija Riyadh-a se sastoji od površinskog tla preko sekvence sedimentarnih stijena, uslojenog vapnenca i vapnenske breče. Duboke stanice su gradjene u vertikalnim iskopima koji su zahtiijevali potporne mjere u tlu, potpuno raspadnutoj stijeni i krškim otvorima u stijeni. Jako raspadnuta do svježa stijena je bila stabilna bez potpore. Potporne mjere u tlu i potpuno raspadnutoj stijeni su uključivale zasijecanje pod uglom, gravitacione zidove, aktivna i pasivna sidra sa prskanim betonom i kontinuirane šipove sa sidrima. Izbor potpornog sistema je ovisio o ograničenjima na lokaciji i osobinama tla. Vrste krških otvora koji su nadjeni u stijenskoj masi uključuju prazne otvore, zapunjene otvore i krške sustave. Potporni sistemi za iskope kroz krške otvore su ovisili o vrsti i veličini otvora i riziku.

Keywords: krš, Riyadh, vapnenac, stabilnost iskopa, potporne mjere, krški otvori.

Introduction

Riyadh Metro Project consisting of 6 lines is being implemented by Riyadh Development Authority (RDA). Lines 1 and 2 of the Project (RMP), being built by a joint venture comprising Bechtel, Almabani, CCC and Siemens (BACS), encompass 63 km of

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track and 50 underground structures including 16 deep underground stations.

Construction of deep underground stations has been carried out in vertical excavations to depths between 20 m and 35 m with a large proportion of the excavations in massive moderately weathered rock not requiring ground support, except in surficial soils and completely weathered rock, or when cavities were encountered.

This paper describes encountered subsurface conditions and excavation stabilization approaches including cavity types and their stabilization.

Subsurface conditions

Geology of the Riyadh central area comprises relatively shallow surficial soils, manmade fill and transported soil of alluvial or aeolian origin, over a sequence of sedimentary rocks, bedded Limestone and Limestone breccia (Powers, et al. 1985, Al-Refai, et al. 1994).

The surficial soils were typically in 1 m to 6 m thickness and weakly cemented except loose sand fill placed around utilities or basements. Some of the basements in the city had been constructed in oversized excavations and the over-excavation was subsequently backfilled. Alluvium thickness was found to be increased at 2 stations and 1 egress shaft in south of Line 1 to depths between 10 and 15m. The thicker Alluvium was mix of clay, silt and sand, dense to very dense, or very stiff to hard.

The limestone rocks were highly or moderately weathered, or fresh, with typically thin completely weathered zone at the contact with the soil. Rock bulk densities measured in laboratory are presented in Figure 1. The completely weathered zone would crumble under firm blows with geological hammer or unravel when the hammer was dragged over vertical cut and we considered it to have soil properties. The less weathered rock was of low to very high strength as presented in Figure 2.

Limestone breccia was massive; bedded Limestone was horizontally bedded, with near vertical joints that were tight and of short persistence. Estimated Geological Strength Index (GSI) of the rock mass was generally between 75 and 90 for both rock types.

Figure 1. Bulk density along Lines 1 and 2.

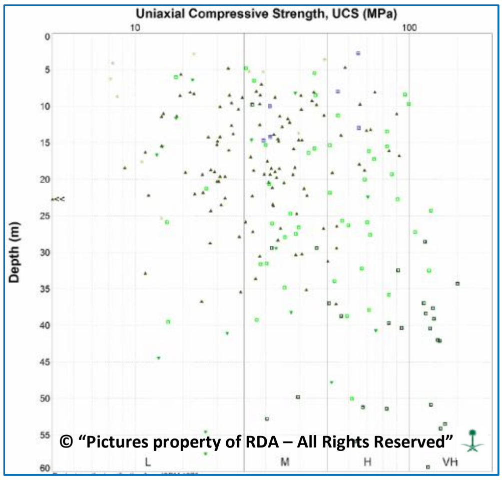

Figure 2. Uniaxial compressive strength of intact rock (strength classification per ISRM 1978).

Some of deep excavations were in dry, but significant number encountered groundwater with several sites in the south having groundwater level only a few meters below the ground surface including the sites with the thick Alluvium.

Besides having to deal with mixed subsurface profiles including weathered rock, excavations in a Limestone dominated landscape usually encounter cavity systems which are generated as a result of percolation and flow of meteoric water. This was also the case in RMP excavations. Figure 3 shows water flowing through a cavity during the excavation of an underground gallery - tunnel section.

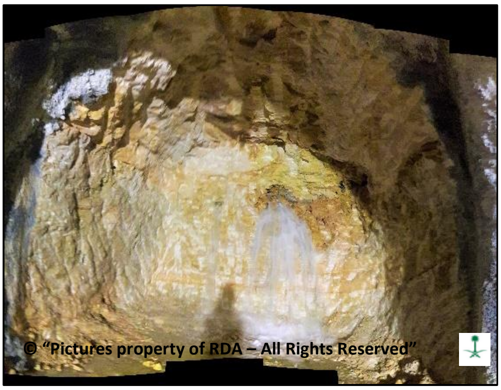

Figure 3. *Water flowing from a cavity intercepted during the excavation of a tunnel section.*

Excavation support

Subsurface conditions at specific station locations were investigated before start of construction using conventional methodology comprised of a combination of drilling, test pitting and geophysical methods. Due to short project schedule, insufficient availability of quality investigation drilling rigs and difficulties in obtaining access in the city environment, the subsurface conditions could not be investigated in detail at majority of structure locations and the conditions had to be verified at the excavation time. This was mostly achieved through geotechnical inspections and mapping by project's geotechnical team. Targeted additional investigations were carried out in special circumstances. Initial designs of support of excavations systems had often to be adjusted to suit site constrains and exposed subsurface conditions.

The surficial cemented soils stood vertical thanks to cementation for prolonged periods of time, but slumped occasionally without notice or after several months, and therefore required stabilization to protect public and construction personnel. The stabilization was dependent on site constrains such as adjacent properties and structures, basements and utilities. The stabilization was in form of battering back at gradients between 1V:1H to 1V:1.5H, or by retaining walls, or by installation of soil nails and shotcrete. Figure 4 shows stabilization of a vertical cut adjacent to a deep building basement.

Figure 4. Soil nail support of sand backfill next to deep basement.

The completely weathered rock zone which had soil properties, was supported using similar methods as the surficial soils.

Excavations through the thick Alluvium (10 to 15m) had to be vertical and were supported either with a system of secant pile walls and anchors, or soil nails and shotcrete. Figure 5 shows an anchored secant pile wall and vertical cut in Bedded Limestone. Figure 6 shows combination of retaining wall and nails supporting vertical excavation in deep alluvium.

Figure 5. Anchored secant pile wall and cut in Bedded Limestone.

Figure 6. Excavation in deep alluvium supported by a combination of retaining wall and nailing.

Highly to moderately weathered or fresh rock was self-supporting in vertical cuts of up to 35 m depth. Such approach was initially adopted based on observations of performance of Riyadh deep excavations for commercial buildings of typical depth of 15 to 20m, and was further substantiated based on stability calculations using Hoek Brown strength criterion for depths of up to 35m. Limit equilibrium and finite element modelling was used for these calculations.

Figure 7 shows stabilization by combination of retaining wall and nailing over a vertical self-supporting cut in Limestone Breccia.

Regular excavation mapping and real time monitoring of movement prisms installed on excavation faces and critical structures was implemented during excavations to confirm design assumptions and control ground risk.

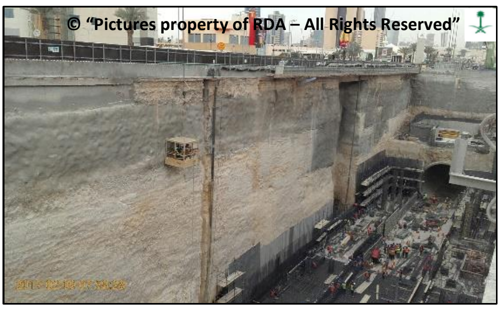

Figure 7. Combination of retaining wall and nailing for soil support above vertical excavation in massive breccia.

Cavity types and approach to remediation in excavations

Amin, et al. 1985 provided "modified engineering classification" for karstic rock terrains in eastern Saudi Arabia which was based on bedded rock – Classes I to V, Limestone surface, Limestone karst, Major karst, Doline karst and Collapsed dolines. We found all the five classes in our excavations, both in massive Limestone breccia and in bedded Limestone.

From perspective of excavation support, two main cavity types were encountered in RMP excavations - empty cavities and infilled cavities. Karstic systems were also encountered and described below.

Empty Cavities. Empty cavities were normally encountered within moderately weathered to fresh, medium strong to strong rock. They appeared as solution cavities with well-defined smooth boundaries and were rarely larger than 5 m. Some of the empty cavities were partially infilled with brecciated material at the base. Typical appearance is shown in Figure 8.

Figure 8. Typical RMP empty cavities.

Empty cavities were considered not to pose high stability risk in general excavations, but were still usually filled with lean concrete as a prudent precautionary measure.

Depending on height of the cavity location above the final excavation level and shape of the cavity floor, soil nailing through the concrete fill was also sometimes applied if the stability of the concrete was of concern.

When the cavities were close to areas supporting heavy lifts or tunnel boring machine breakthroughs, the risk to the project was high. The typical remediation options included filling of the cavity with gravity grout or lean concrete or low-pressure grouting techniques, combined with nailing and shotcrete.

Infilled Cavities. Infilled cavities were much more frequently encountered, typically within any of the limestone rock types and strength, although less commonly in completely weathered rock. Extent of infilled cavities was normally well defined, but it was more difficult to identify when encountered in rock with higher degree of weathering.

The infill material consisted of weakly cemented soil, either originating from collapsing completely weathered limestone rock or from transported Quaternary material. The collapsed material was poorly cemented clay, silt, sand and gravel thought to be deposited in-situ simultaneously to the cavity formation. Example of such infill is shown in Figures 9 and 10. The Quaternary material was of alluvial and aeolian origins, dominated by sand with some clay and silt, weakly cemented, loose to medium dense (shown in Figures 11 and 12). It infilled solution cavities after being transported by percolating water.

Figure 9. Infilled cavity exposing collapsed material.

Figure 10. Stabilization of infilled cavity.

Excavation stabilization aimed to reinforce the infilled soil. Large majority of cavities were of dimensions not exceeding 5m and stabilized using standard nailing and shotcrete measures that were provided on support of excavation drawings,

Where cavity dimensions exceeded design dimensions, or where conditions were deemed not to represent design assumptions, the stabilization measures where designed by on-site geotechnical team. Soil nails and shotcrete were sized according to cavity extent, material strength and loads applied.

For a case where a large extent cavity was found in an excavation under foundations of an adjacent high-rise building, bar anchors were sized considering the building loads. Low pressure grouting at 1.5 to 3 bars was carried out through anchor installation holes and anchors were prestressed to reduce risk of excavation and tower movements. Drilling rates during nail installation were used to infer where competent rock behind the infill was encountered and to optimize nail length.

Figure 11. Large infilled cavity exposing alluvial/ aeolian soil above tunnel crown in station excavation.

Figure 12. Infilled cavity exposing alluvial/ aeolian soil (4 m width).

Grouting and prestressed cable anchors were successfully used in another case to stabilize an excavation through infilled cavity where monitoring prisms experienced continued movement after installation of soil nails and shotcrete. Movements that occurred after soil nails installation potentially indicated collapsing cavity.

Karstic Systems. Irregular karstic systems of interconnected vugs, channels and voids were also exposed in excavations and typically not stabilized relying on mechanical connection between solid rock matrix to resist gravity forces. However, low pressure grouting and nailing with shotcrete was used in areas supporting heavy machinery or excavations prepared for penetration of tunnel boring machines, to control the risk. Figure 13 shows a karstic system exposure in excavation at one of RMP stations.

Figure 13. Karstic system.

Conclusion

The paper has presented subsurface conditions and approach to stabilization measures for 20 m to 35 m deep construction excavations in Riyadh karstic environment which included surficial soils over a sequence of Limestone breccia and bedded Limestone, empty cavities, infilled cavities and karstic systems.

Acknowledgments

We wish to thank Riyadh Development Authority (RDA) for their support and opportunity to work on Riyadh Metro Project.

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