

# Shazar Caverns, Israel

Dr. Roberto Schuerch  
ETH Zürich, 12.12.2019



## TABLE OF CONTENTS

**INTRODUCTION**

**DESIGN CHALLENGES & HAZARDS**

**CAVERNS DESIGN**

**HAUMA RAILWAY STATION**

**CONSTRUCTION EXPERIENCE**

**CONCLUSIONS**

## INTRODUCTION

### INTRODUCTION

DESIGN CHALLENGES & HAZARDS

CAVERNS DESIGN

HAUMA RAILWAY STATION

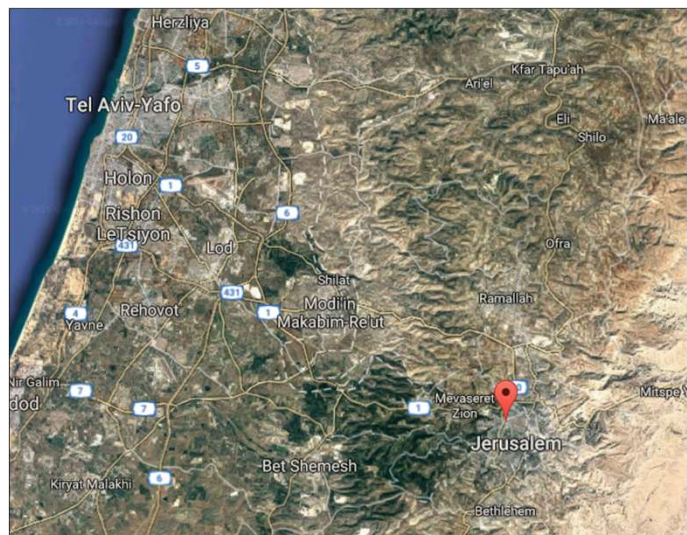
CONSTRUCTION EXPERIENCE

CONCLUSIONS

3 | 12.12.2019 | Shazar Caverns, Israel



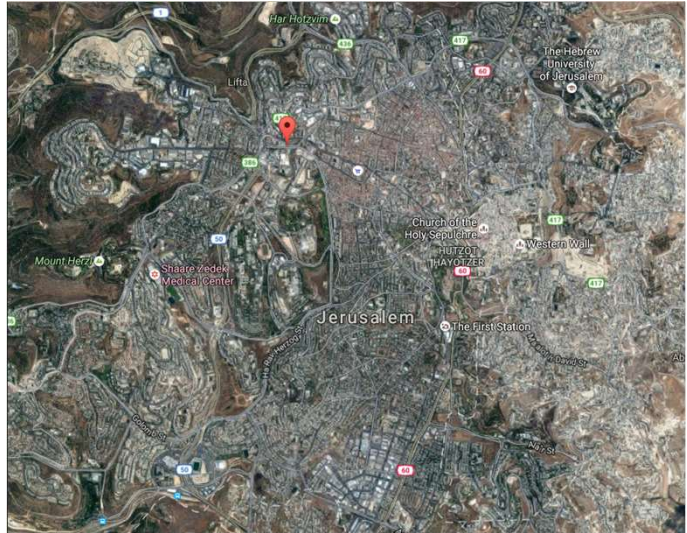
## INTRODUCTION



4 | 12.12.2019 | Shazar Caverns, Israel



## INTRODUCTION



5 | 12.12.2019 | Shazar Caverns, Israel

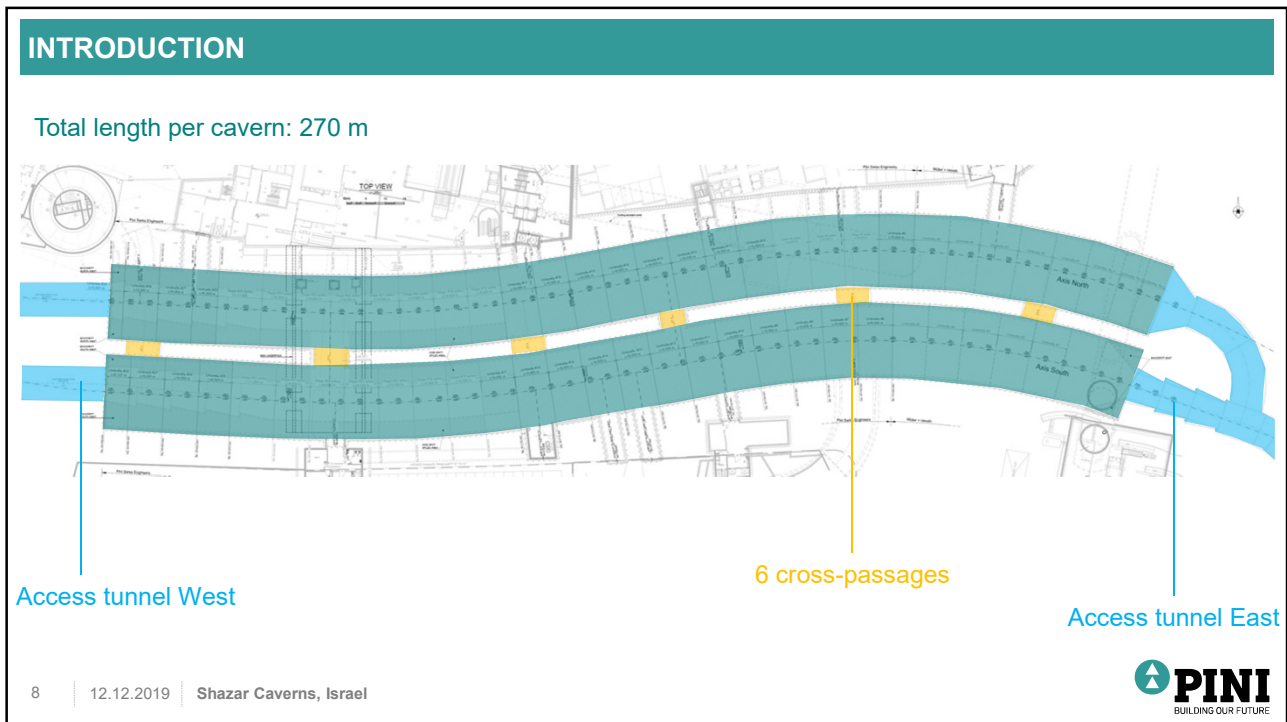
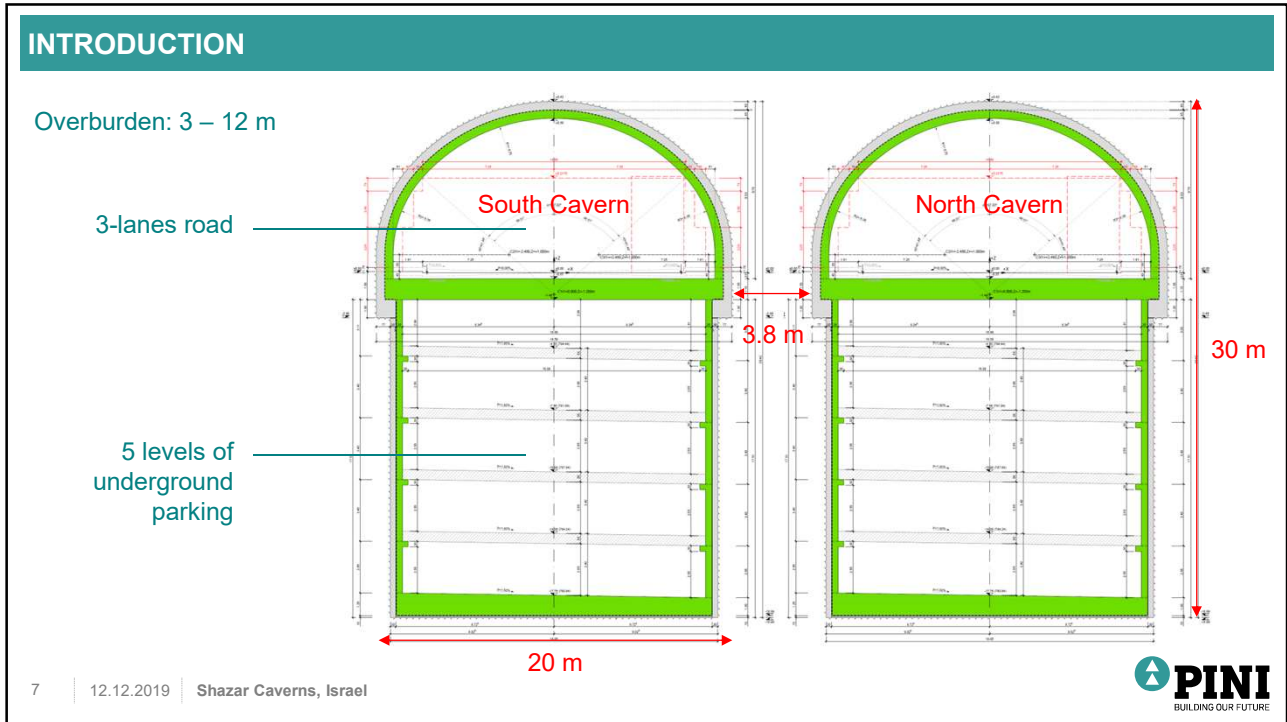


## INTRODUCTION



6 | 12.12.2019 | Shazar Caverns, Israel





### INTRODUCTION

Hauma railway station

Existing underground buildings

9 | 12.12.2019 | Shazar Caverns, Israel

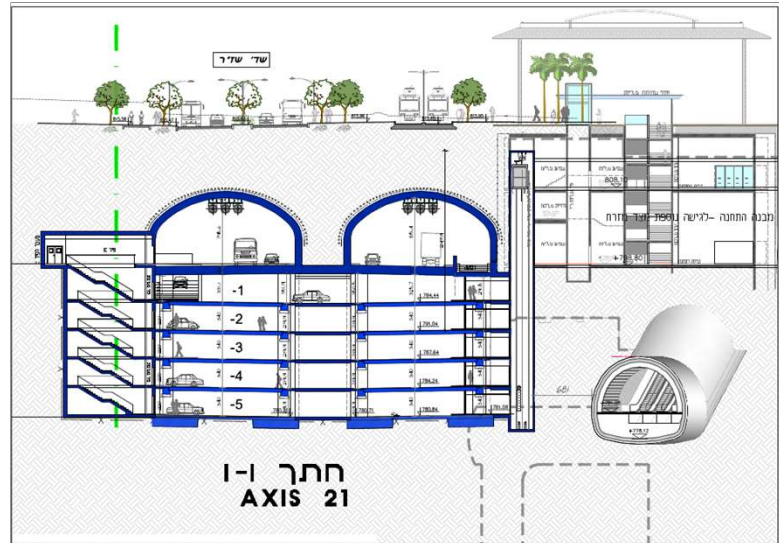
### INTRODUCTION

Hauma railway station

10 | 12.12.2019 | Shazar Caverns, Israel

## INTRODUCTION

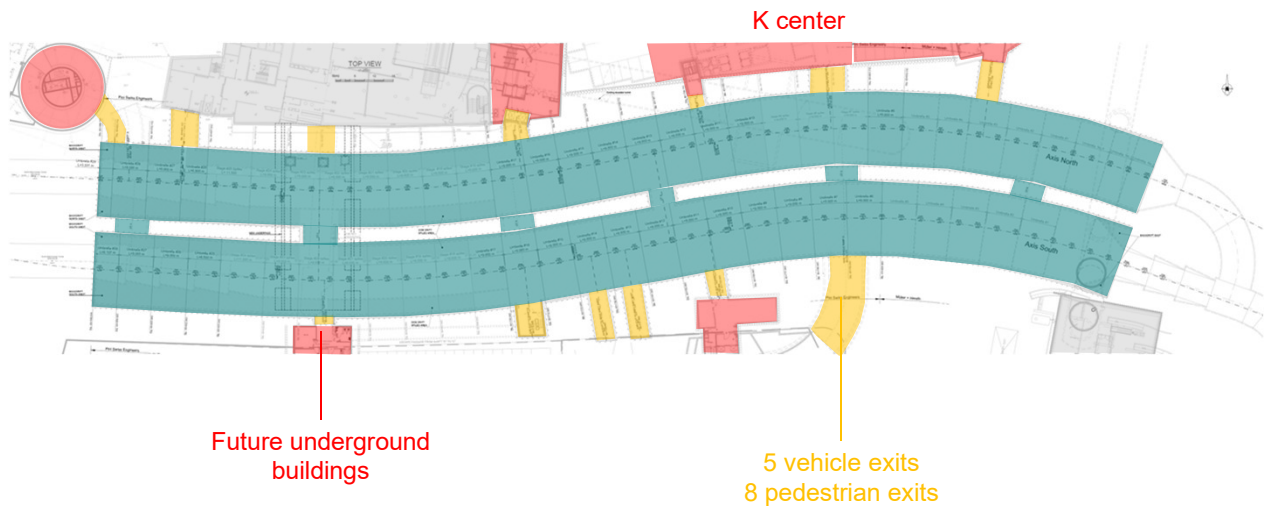
### Hauma railway station



11 | 12.12.2019 | Shazar Caverns, Israel



## INTRODUCTION

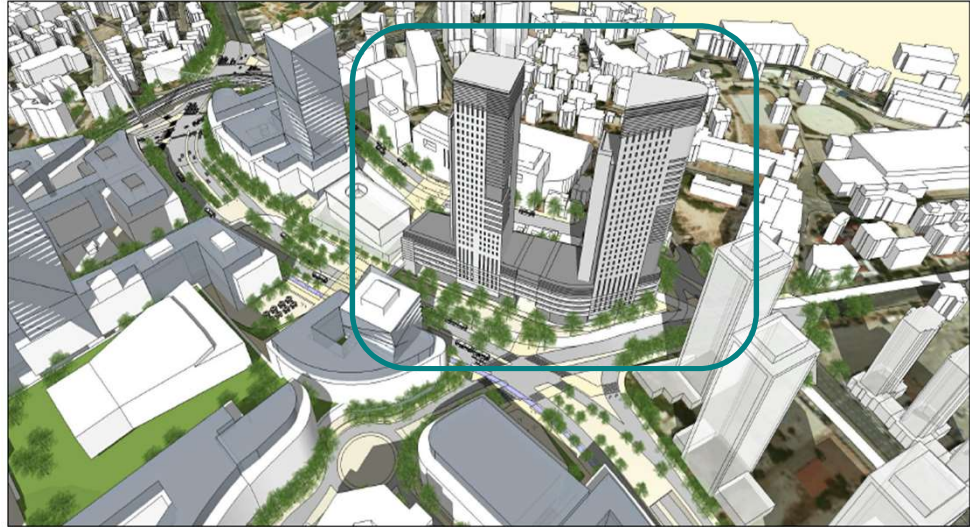


12 | 12.12.2019 | Shazar Caverns, Israel



## INTRODUCTION

### K center



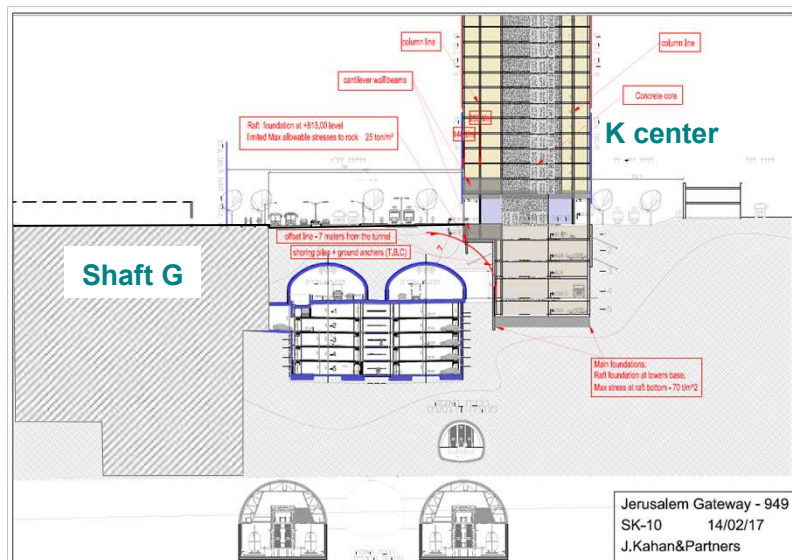
13 | 12.12.2019 | Shazar Caverns, Israel



## INTRODUCTION

### K center

- 2 buildings: 34 floors above street level (140 m height)
- 5 basement levels
- Distance from Tunnel: ~7 m
- Type of Foundation: Raft



14 | 12.12.2019 | Shazar Caverns, Israel

Jerusalem Gateway - 949  
SK-10 14/02/17  
J.Kahan&Partners



## INTRODUCTION

- Calatrava bridge
- West portal of the access tunnel
- Hauma railway station
- Shazar road
- West portal of the access tunnel



15 | 12.12.2019 | Shazar Caverns, Israel



## INTRODUCTION

### West access tunnel and Calatrava bridge



16 | 12.12.2019 | Shazar Caverns, Israel





## INTRODUCTION

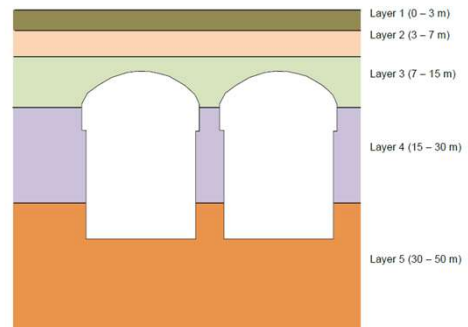
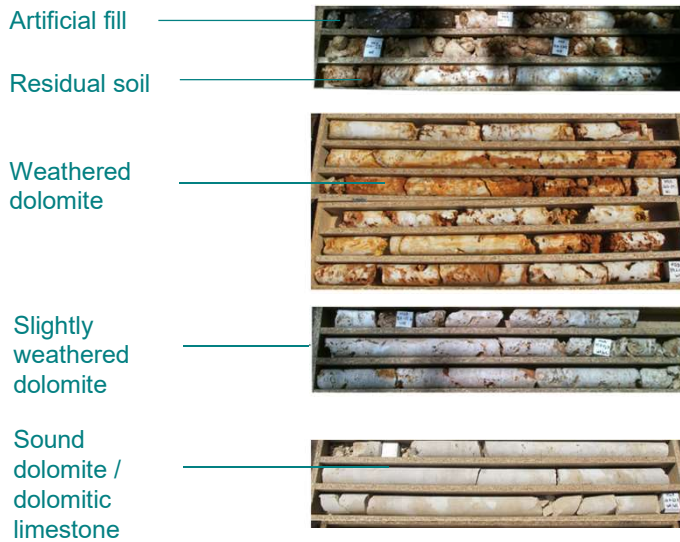
### East access tunnel



17 | 12.12.2019 | Shazar Caverns, Israel



## INTRODUCTION – GEOLOGICAL CONDITIONS



		$E$ [MPa]	$\nu$ [-]	$\varphi$ [°]	$\psi$ [°]	$c$ [kPa]	UCS [kPa]	$\gamma$ [kN/m <sup>3</sup> ]	$K_0$ [-]
Layer 1	Artificial filling	50	0.3	30	10	5	17	22	0.5
Layer 2	Residual soil (>50% clay)	250	0.3	35	15	40	153	22	0.5
Layer 3	Weathered dolomite/dolomitic limestone	500	0.25	35	15	260	1,000	24	0.5
Layer 4	Slightly weathered dolomite/dolomitic limestone	3,000	0.25	35	15	1,562	6,000	25	0.5
Layer 5	Sound dolomite/dolomitic limestone	20,000	0.25	35	15	10,411	40,000	25	0.5

18 | 12.12.2019 | Shazar Caverns, Israel



## INTRODUCTION – GEOLOGICAL CONDITIONS



19 | 12.12.2019 | Shazar Caverns, Israel



## DESIGN CHALLENGES & HAZARDS

INTRODUCTION

**DESIGN CHALLENGES & HAZARDS**

CAVERNS DESIGN

HAUMA RAILWAY STATION

CONSTRUCTION EXPERIENCE

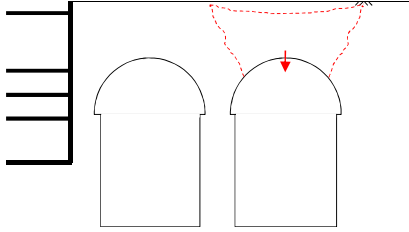
CONCLUSIONS

20 | 12.12.2019 | Shazar Caverns, Israel

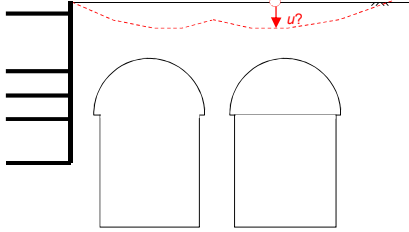


### DESIGN CHALLENGES & HAZARDS

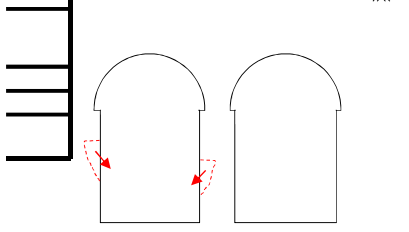
**Crater formation at the road surface**



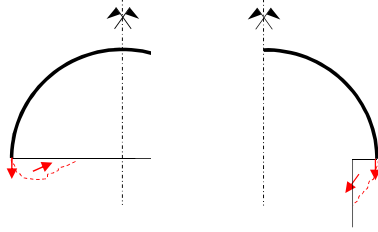
**Excessive road settlements**




**Sliding of rock blocks**




**Instability of the top-heading foundation**



21 | 12.12.2019 | Shazar Caverns, Israel



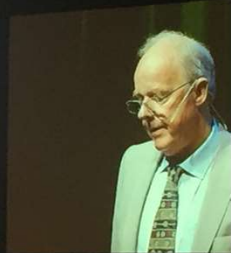
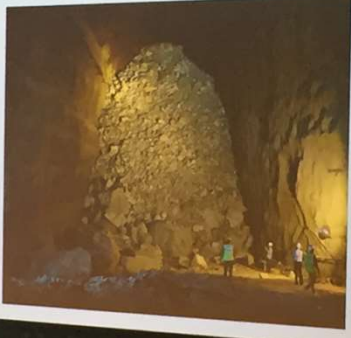
### DESIGN CHALLENGES & HAZARDS




**NEW COLLAPSE. TOTAL OF 70,000 m<sup>3</sup>.**  
CAVITY L x H x W:  
(50-60)m x (40-50)m x (30-35)m  
HAS TO BE STABILIZED.  
THEN VICTIMS CAN BE RECOVERED.

**ATTEMPT TO REMOVE FALLEN ROCK**  
(approx. 15,000 m<sup>3</sup>)

**NOTE (EXTRA) DESTRUCTION OF STEEL**  
SETS IN THE 'LEFT' ARCH.

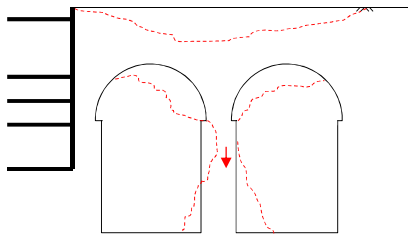


22 | 12.12.2019 | Shazar Caverns, Israel

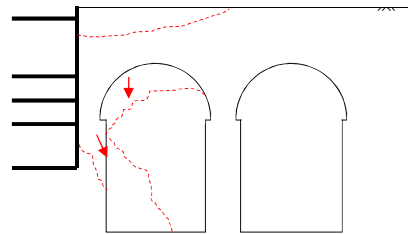


## DESIGN CHALLENGES & HAZARDS

Instability of the rock pillar between the caverns



Instability of the rock pillar between the cavern and buildings



Central pillar "thin" compared to its height!

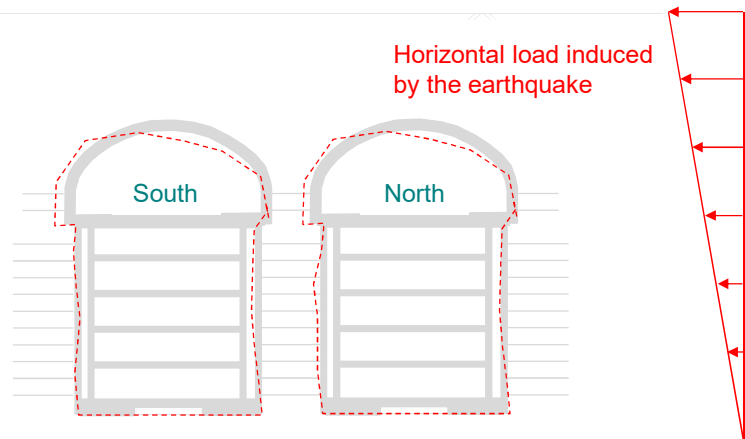
23 | 12.12.2019 | Shazar Caverns, Israel



## DESIGN CHALLENGES & HAZARDS

Instability of the pillar

Stage: before trench excavation




24 | 12.12.2019 | Shazar Caverns, Israel




### DESIGN CHALLENGES & HAZARDS

**Instability of the pillar**

*Stage: during trench excavation*



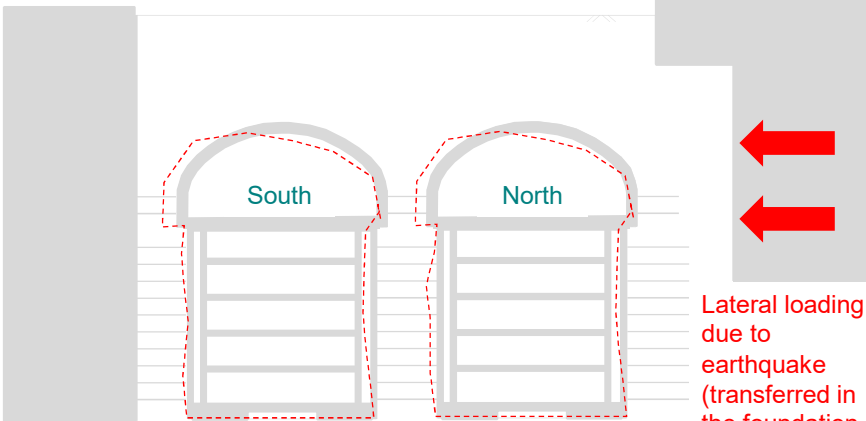
25 | 12.12.2019 | Shazar Caverns, Israel



### DESIGN CHALLENGES & HAZARDS


**Instability of the pillar**

*Stage: after buildings construction*



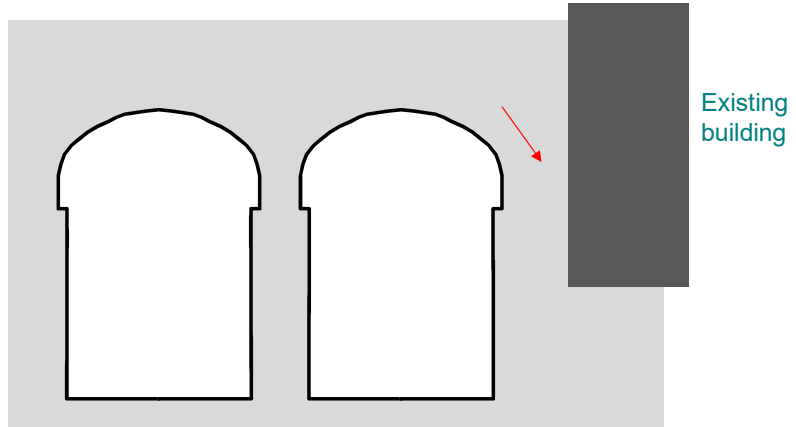
Lateral loading due to earthquake (transferred in the foundation area of the k-center)

26 | 12.12.2019 | Shazar Caverns, Israel



## DESIGN CHALLENGES & HAZARDS

### Damages of the existing structures



- Additional load may cause inadmissible deformation or damages to the existing buildings

27 | 12.12.2019 | Shazar Caverns, Israel



## CAVERNS DESIGN

INTRODUCTION

DESIGN CHALLENGES & HAZARDS

**CAVERNS DESIGN**

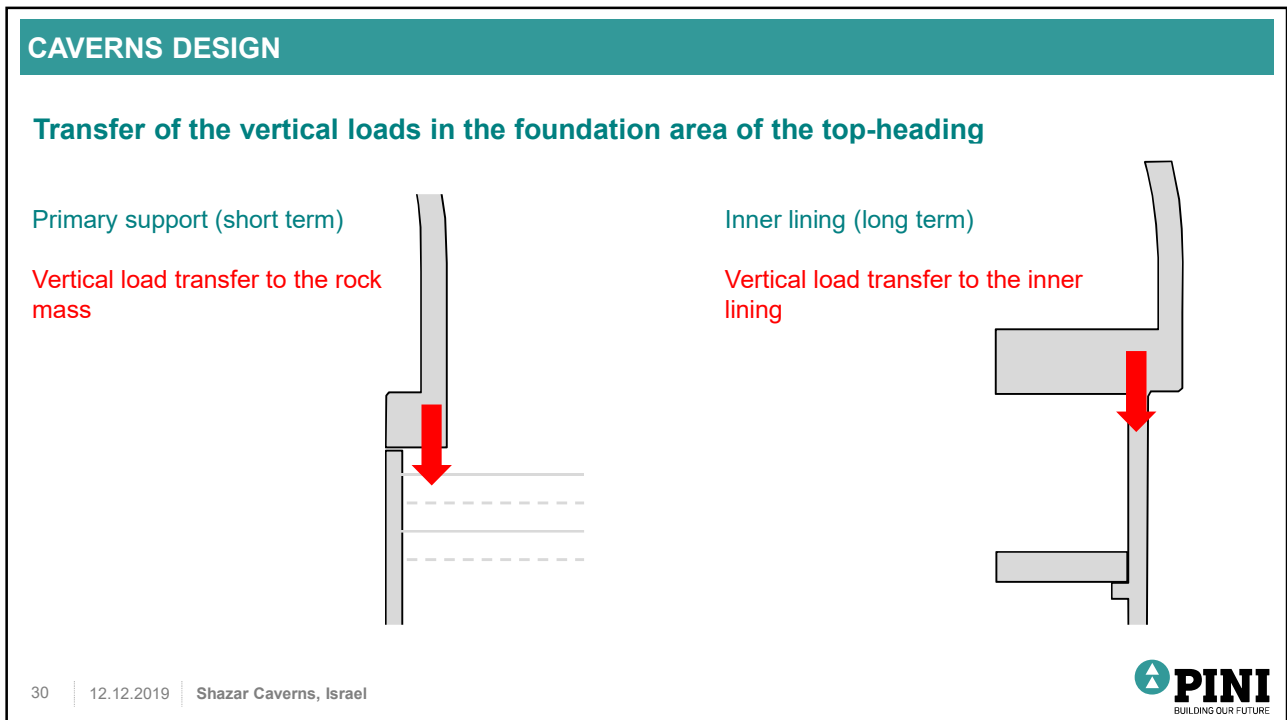
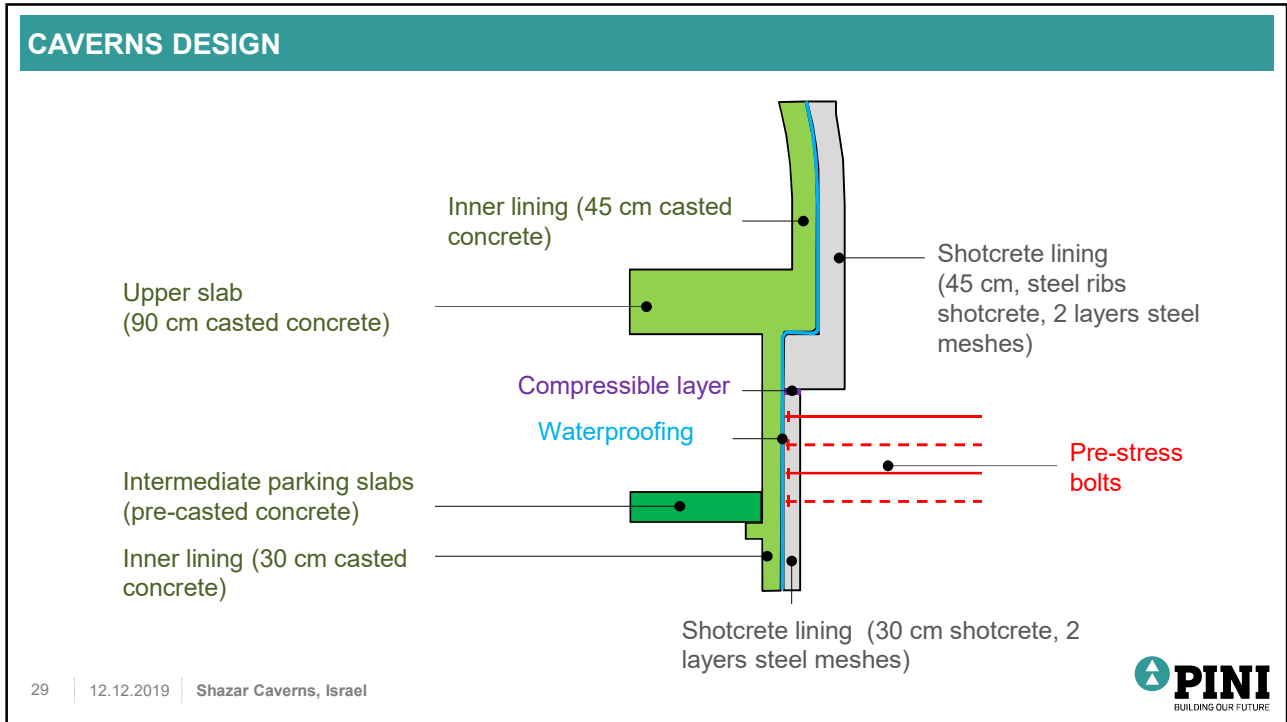
HAUMA RAILWAY STATION

CONSTRUCTION EXPERIENCE

CONCLUSIONS

28 | 12.12.2019 | Shazar Caverns, Israel

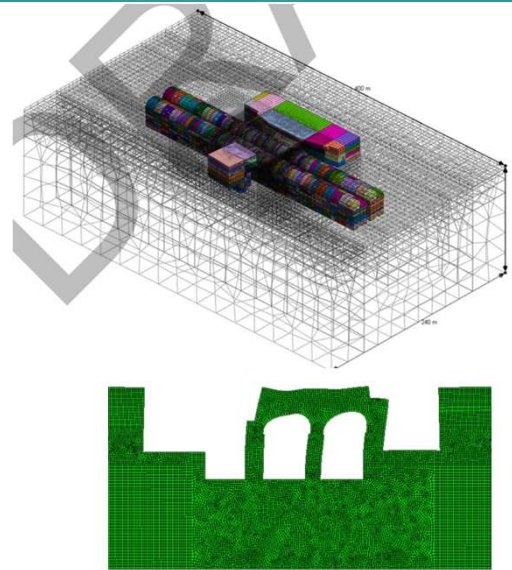




## CAVERNS DESIGN

### Computational methods

- Static analysis (2D and 3D models)
- Seismic analysis (dynamic and pseudo-static 2D models)
- Validation through simplified analytical models

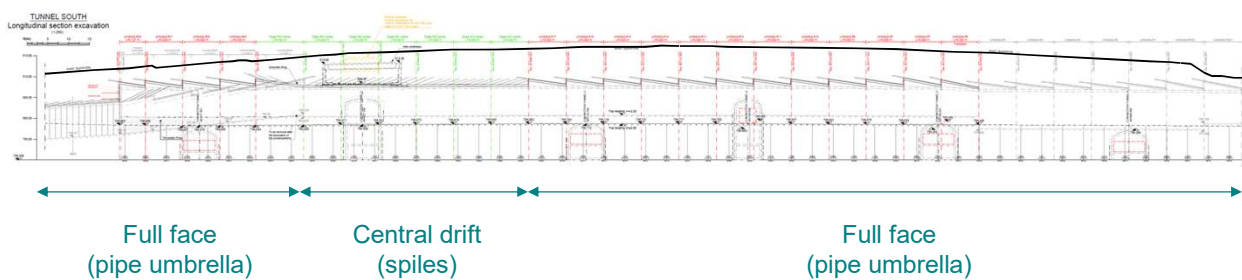


31 | 12.12.2019 | Shazar Caverns, Israel



## CAVERNS DESIGN

### Excavation of the top heading



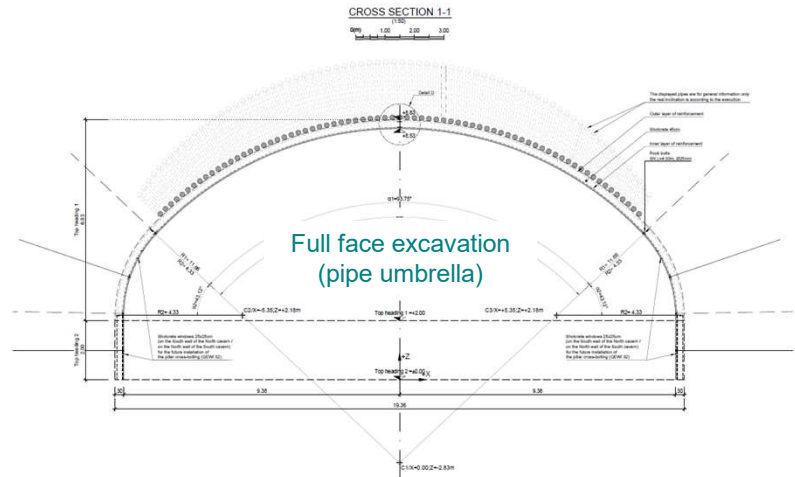
32 | 12.12.2019 | Shazar Caverns, Israel





## CAVERNS DESIGN

### Excavation of the top heading



33 | 12.12.2019 | Shazar Caverns, Israel



## CAVERNS DESIGN

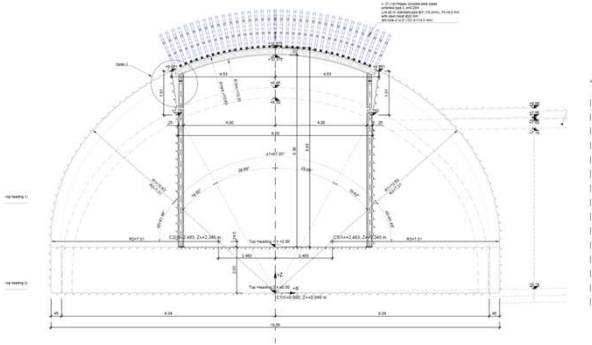


34 | 12.12.2019 | Shazar Caverns, Israel

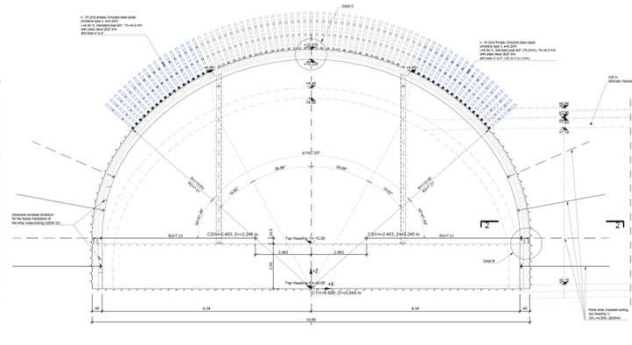


## CAVERNS DESIGN

### Excavation of the top heading



Central drift



Enlargement

35 | 12.12.2019 | Shazar Caverns, Israel



## CAVERNS DESIGN



36 | 12.12.2019 | Shazar Caverns, Israel



**CAVERNS DESIGN**

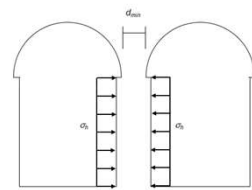
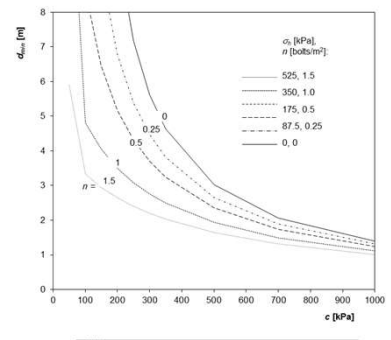
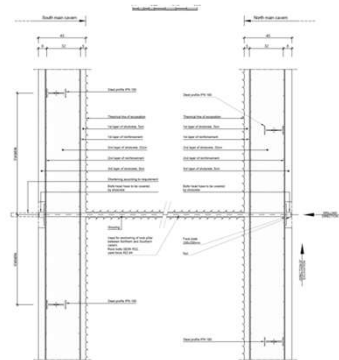
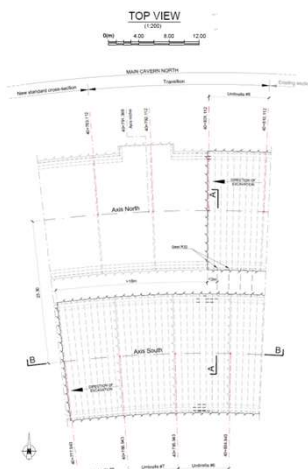


37 | 12.12.2019 | Shazar Caverns, Israel



**CAVERNS DESIGN**

**Cross-bolting between the caverns**

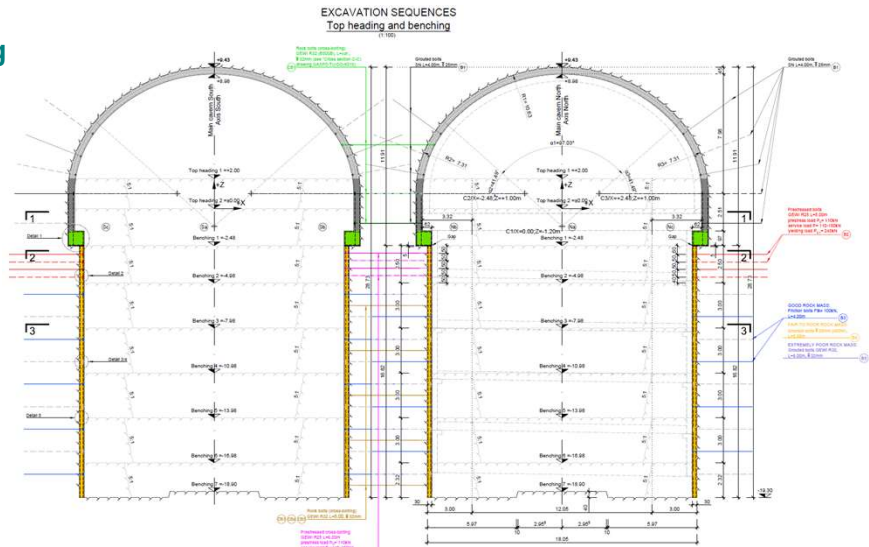


38 | 12.12.2019 | Shazar Caverns, Israel



## CAVERNS DESIGN

### Excavation of the benching



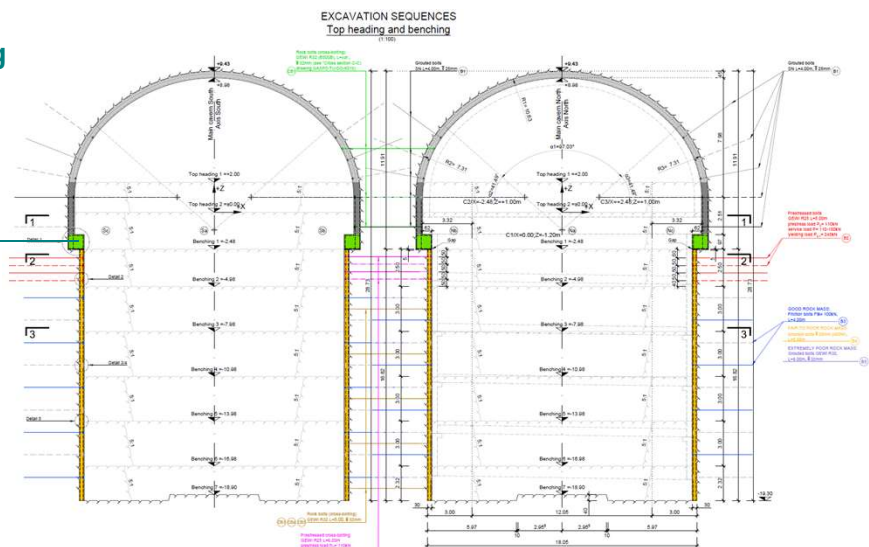
39 | 12.12.2019 | Shazar Caverns, Israel



## CAVERNS DESIGN

### Excavation of the benching

Longitudinal foundation beam



40 | 12.12.2019 | Shazar Caverns, Israel



## CAVERNS DESIGN



41 | 12.12.2019 | Shazar Caverns, Israel



## CAVERNS DESIGN



42 | 12.12.2019 | Shazar Caverns, Israel



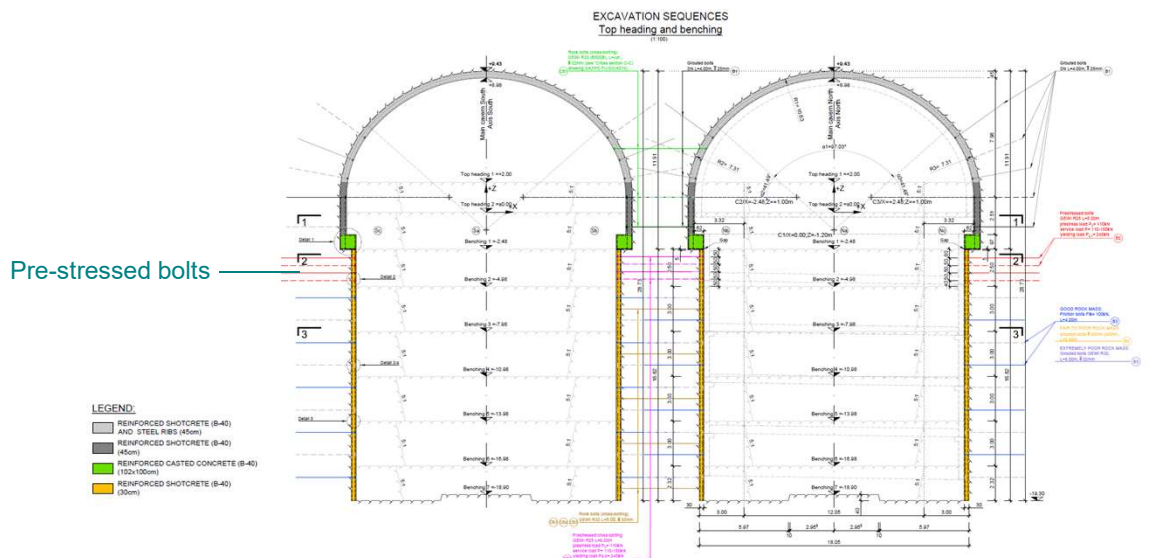
CAVERNS DESIGN



43 | 12.12.2019 | Shazar Caverns, Israel



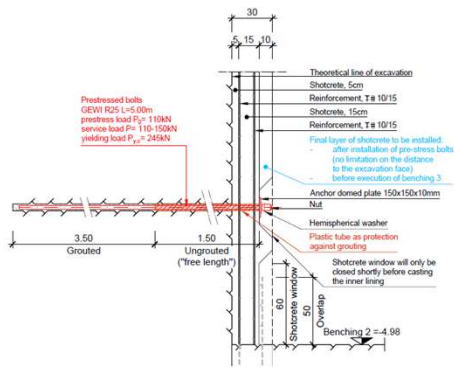
CAVERNS DESIGN



44 | 12.12.2019 | Shazar Caverns, Israel



## CAVERNS DESIGN



45 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION

INTRODUCTION

DESIGN CHALLENGES & HAZARDS

CAVERNS DESIGN

**HAUMA RAILWAY STATION**

CONSTRUCTION EXPERIENCE

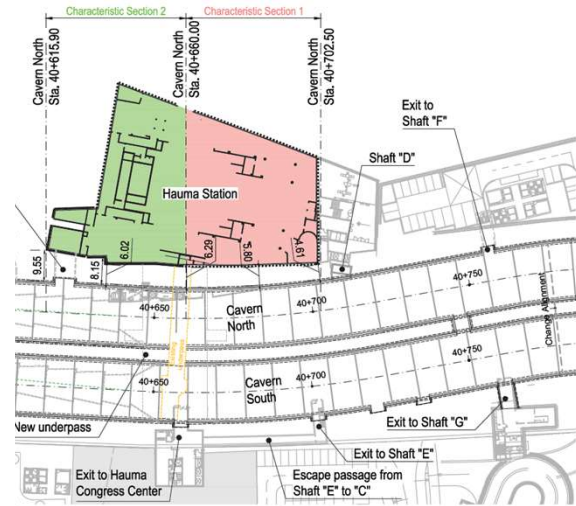
CONCLUSIONS

46 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION

- Length of the critical section : 90 m
- Minimum distance to the caverns: 4.5 m



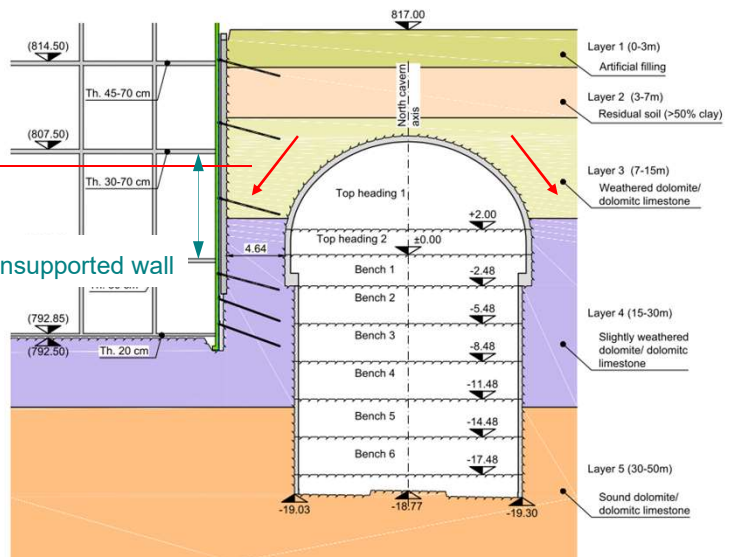
47 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION

Resultant of stresses prevailing in (and close to) the lateral pillar

8.5 m high unsupported wall



48 | 12.12.2019 | Shazar Caverns, Israel





## HAUMA RAILWAY STATION

8.5 m high unsupported wall



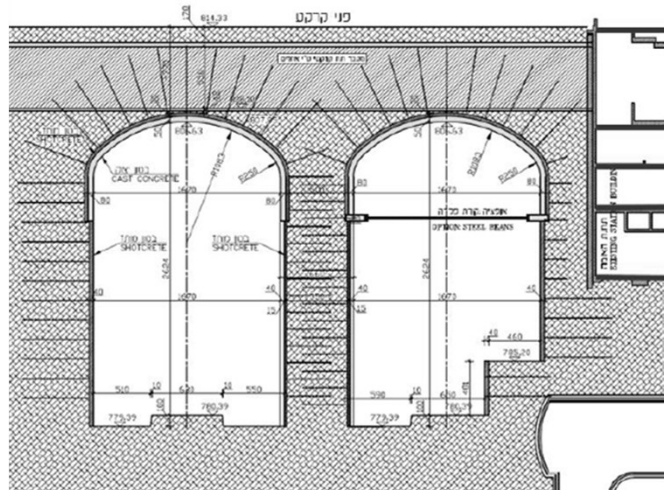
49 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION

### Designer 1 – Original design

- Casting of the inner lining of the top-heading before benching
  - Installation of post-tensioned beams before excavation of the benching
- Conclusion: project not feasible without damaging the station
- Change of designer



50 | 12.12.2019 | Shazar Caverns, Israel

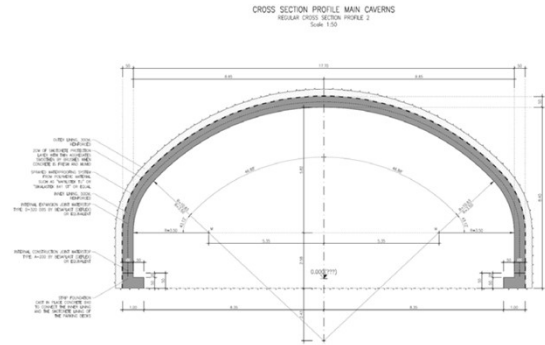


## HAUMA RAILWAY STATION

### Designer 2 – New design concept

- Casting of a thicker concrete lining before excavation of the benching
- Change of the top-heading geometry
- Change of the alignment (increase of the distance by about 2 m)

- Conclusion: project not feasible without damaging the station
- Change of designer



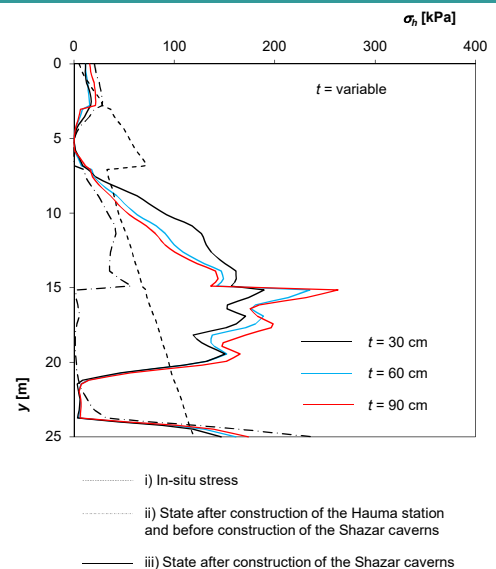
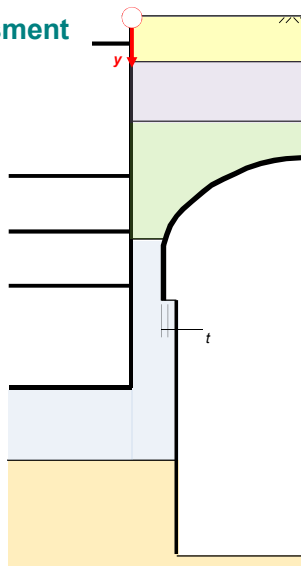
51 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION

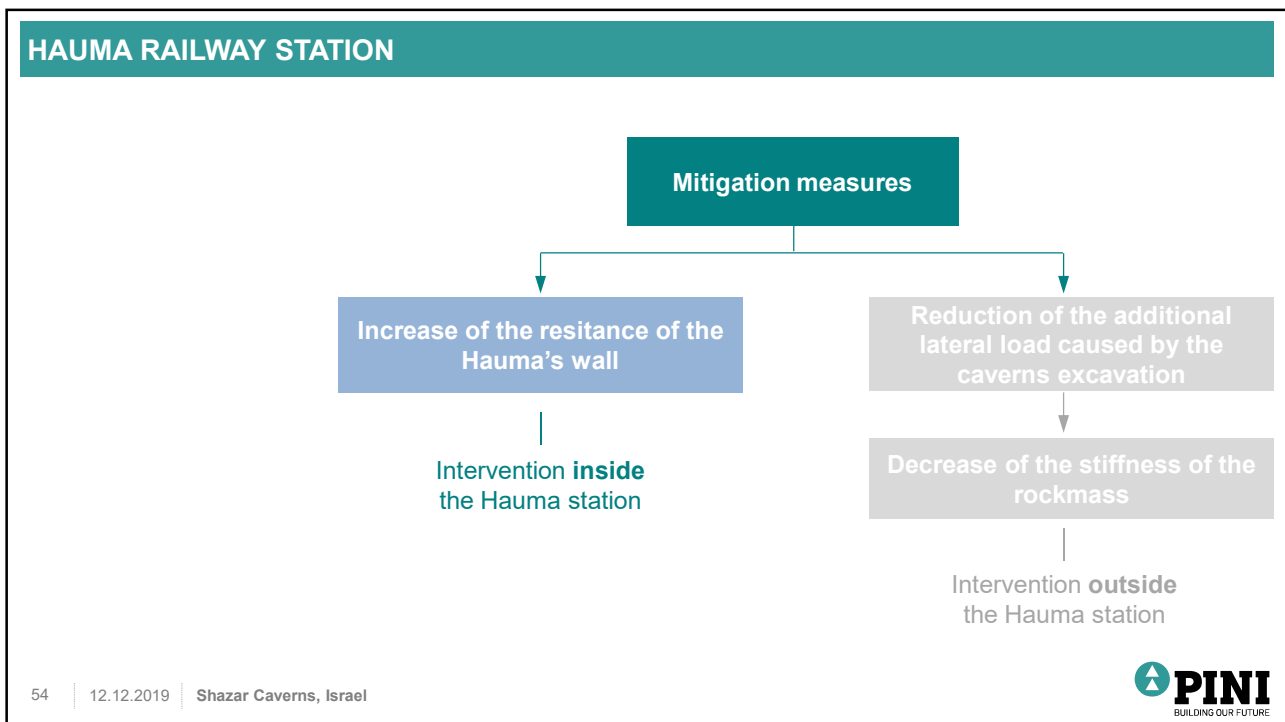
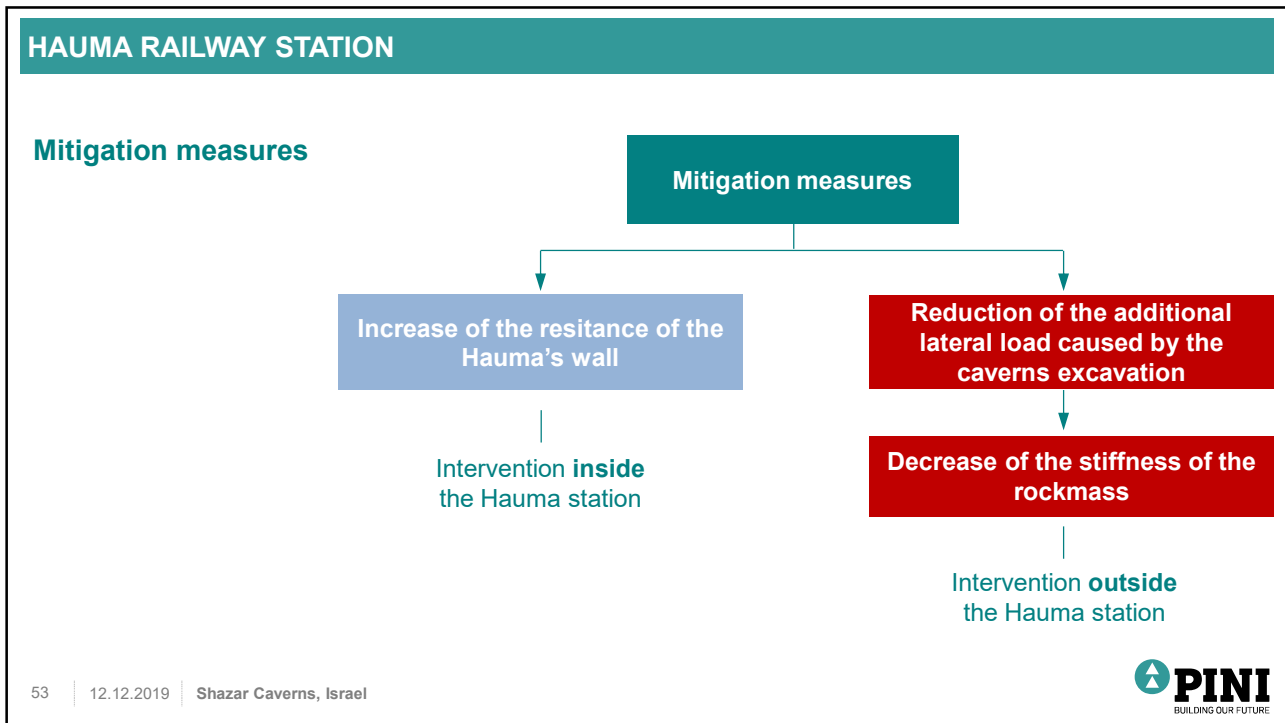
### Pini Swiss Engineers – Assessment

- Rock mass much stiffer than the support; not possible to decrease the load on the station by increasing the thickness of the support/inner lining
- Alternative solutions required



52 | 12.12.2019 | Shazar Caverns, Israel



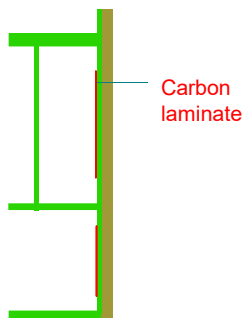


## HAUMA RAILWAY STATION

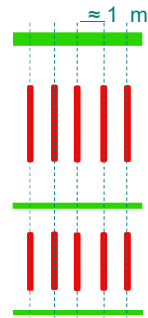
### Increase the resistance of the Hauma's wall

Solution 1: Strengthening of the Hauma's wall with carbon laminate or steel plates

Cross-section



Front view



[http://renobeton.ch/v1.0/image/s/04\\_LAMELLE/LAMELLE-2de.jpg](http://renobeton.ch/v1.0/image/s/04_LAMELLE/LAMELLE-2de.jpg)

55 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION

### Mitigation measures

Increase of the resistance of the Hauma's wall

Intervention **inside** the Hauma station

Reduction of the additional lateral load caused by the caverns excavation

Decrease of the stiffness of the rockmass

Intervention **outside** the Hauma station

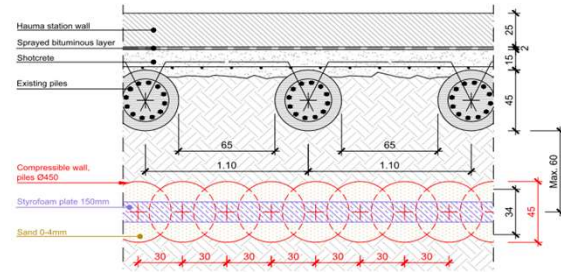
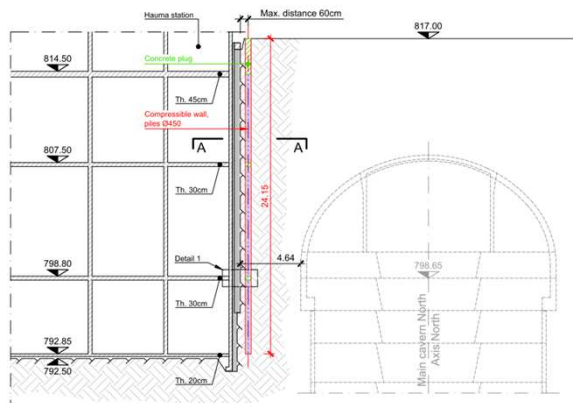
56 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION

### Decrease of the additional lateral load caused by the caverns excavation

#### Solution 2: Disconnecting the rock mass from the Hauma's wall



Details of the compressible layer, horizontal cross section.

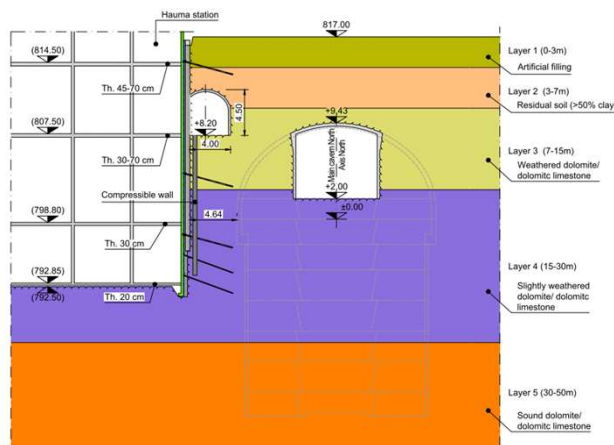
57 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION

### Decrease of the additional lateral load caused by the caverns excavation

#### Solution 3: Disconnecting the rock mass from the Hauma's wall from an auxiliary tunnel



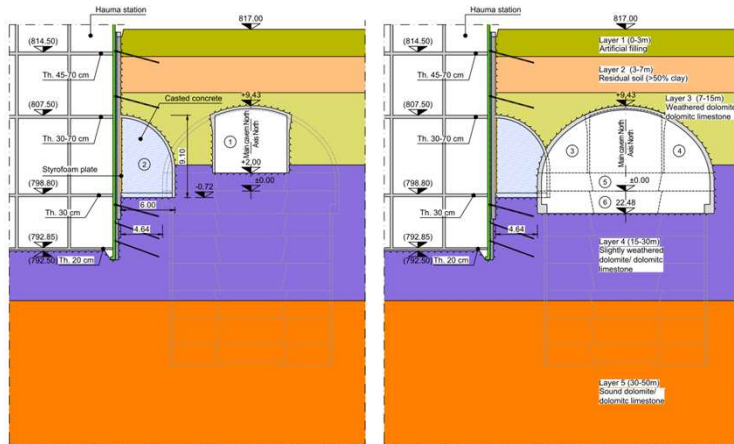
58 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION

### Decrease of the additional lateral load caused by the caverns excavation

#### Solution 4: Installation of a compressible layer from a side drift

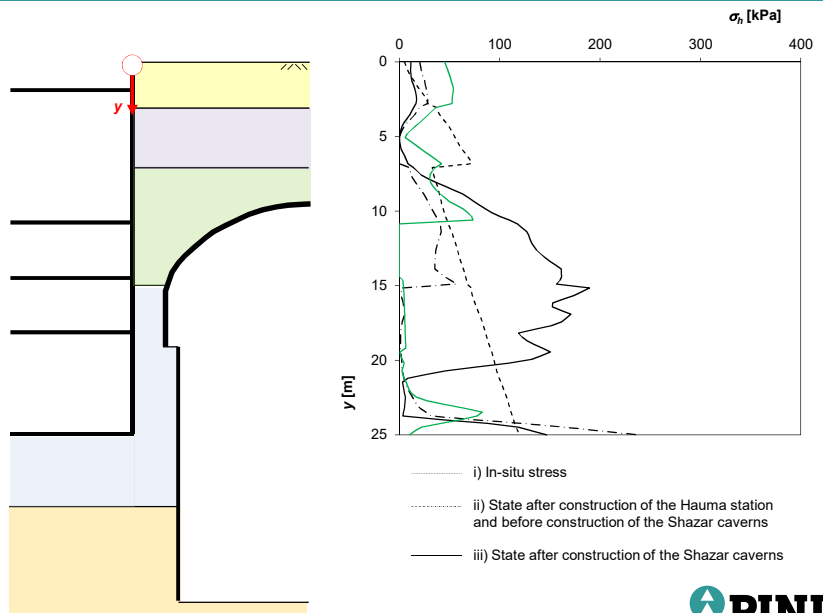


59 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION

Clear reduction of the horizontal load on the wall of the station



60 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION

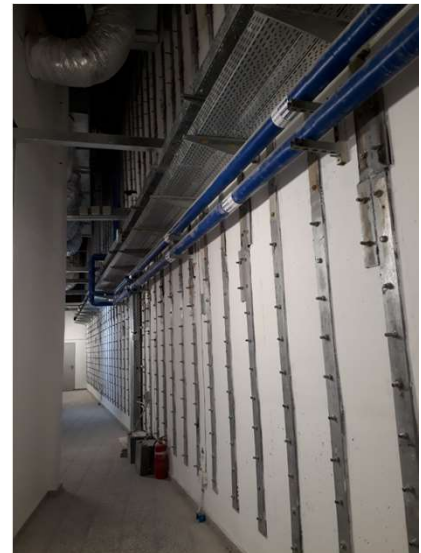
### Selected mitigation measure

- Reinforcement of the wall of the station by means of steel plates (solution 1)
- Intensive monitoring of the wall behavior during excavation (tiltmeter, extensometers, high-precision distance meter by means of laser)
- Excavation concept: top-heading in two phases (1<sup>st</sup> central drift + 2<sup>nd</sup> enlargement)

61 | 12.12.2019 | Shazar Caverns, Israel



## HAUMA RAILWAY STATION



62 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE

INTRODUCTION

DESIGN CHALLENGES & HAZARDS

CAVERNS DESIGN

HAUMA RAILWAY STATION

**CONSTRUCTION EXPERIENCE**

CONCLUSIONS

63 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE

### Excavation activities

- Excavation top-heading: 01.04.2017 – 01.08.2018
- Excavation benching: 01.02.2018 – 01.07.2019
- Inner lining: 01.08.2019 – ongoing
- Operation of the cavern: End of 2022

64 | 12.12.2019 | Shazar Caverns, Israel





## CONSTRUCTION EXPERIENCE

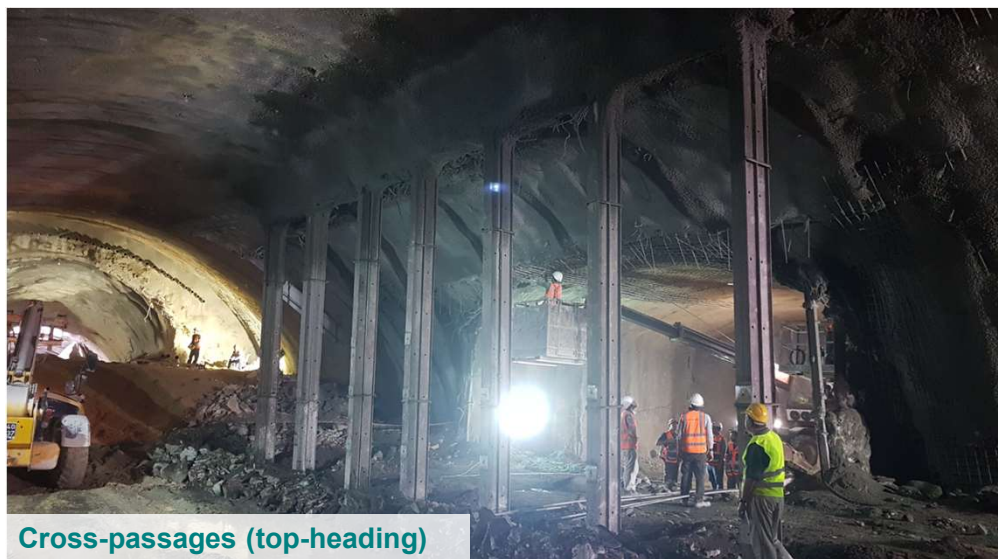


Cross-passages (top-heading)

65 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE



Cross-passages (top-heading)

66 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE



Benching (level 2 of 7)

67 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE



Benching (level 3 of 7)

68 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE



Benching (level 7 of 7; exit to Shaft G)

69 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE



Benching (level 7 of 7)

70 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE



**A bit of luck helps...high pressure water pipe (not mapped!)**

71 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE



**Dealing with karstic cavities**

72 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE



Dealing with karstic cavities

73 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE

Filled with more than 750 m<sup>3</sup> of concrete



Dealing with karstic cavities

74 | 12.12.2019 | Shazar Caverns, Israel



## CONSTRUCTION EXPERIENCE

**Celebration after successful top—heading enlargement of the tunnel section running close to the Hauma station!**



75 | 12.12.2019 | Shazar Caverns, Israel



## CONCLUSIONS

INTRODUCTION

DESIGN CHALLENGES & HAZARDS

CAVERNS DESIGN

HAUMA RAILWAY STATION

CONSTRUCTION EXPERIENCE

**CONCLUSIONS**

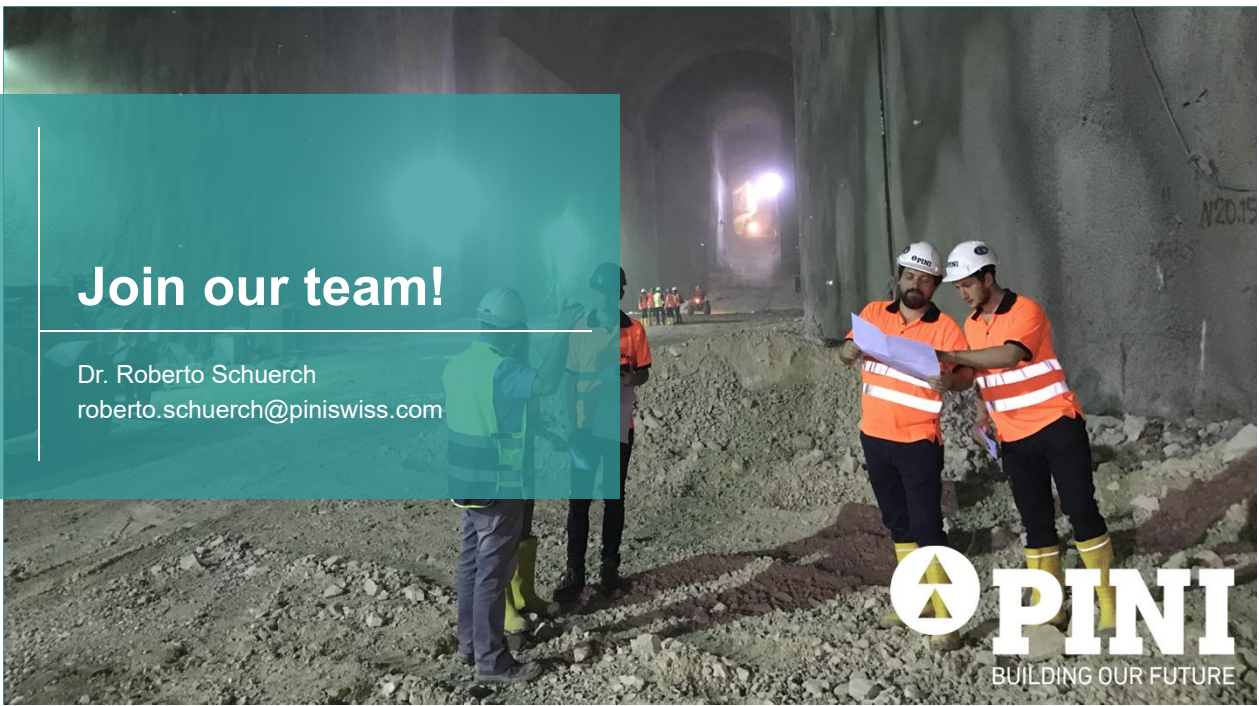
76 | 12.12.2019 | Shazar Caverns, Israel



## CONCLUSIONS


- Unique project combining large size caverns, small size rock pillar and strong interaction with existing and future buildings/infrastructures
- Extremely high pressure on the designer (feasibility concern leading to a change of designer during construction)
- Success factors:
  - (i) think different (elaboration of a completely new structural concept within an extremely short time)
  - (ii) site supervision for a correct implementation of the design solution
  - (iii) excellent collaboration between Designer, Owner and Contractor

THANK YOU FOUR YOUR ATTENTION



**Join our team!**

Dr. Roberto Schuerch  
[roberto.schuerch@piniswiss.com](mailto:roberto.schuerch@piniswiss.com)

 **PINI**  
BUILDING OUR FUTURE