Risk assessment of collapse in shallow caverns using numerical modeling of block interactions with DDA: Suggested approach and case studies

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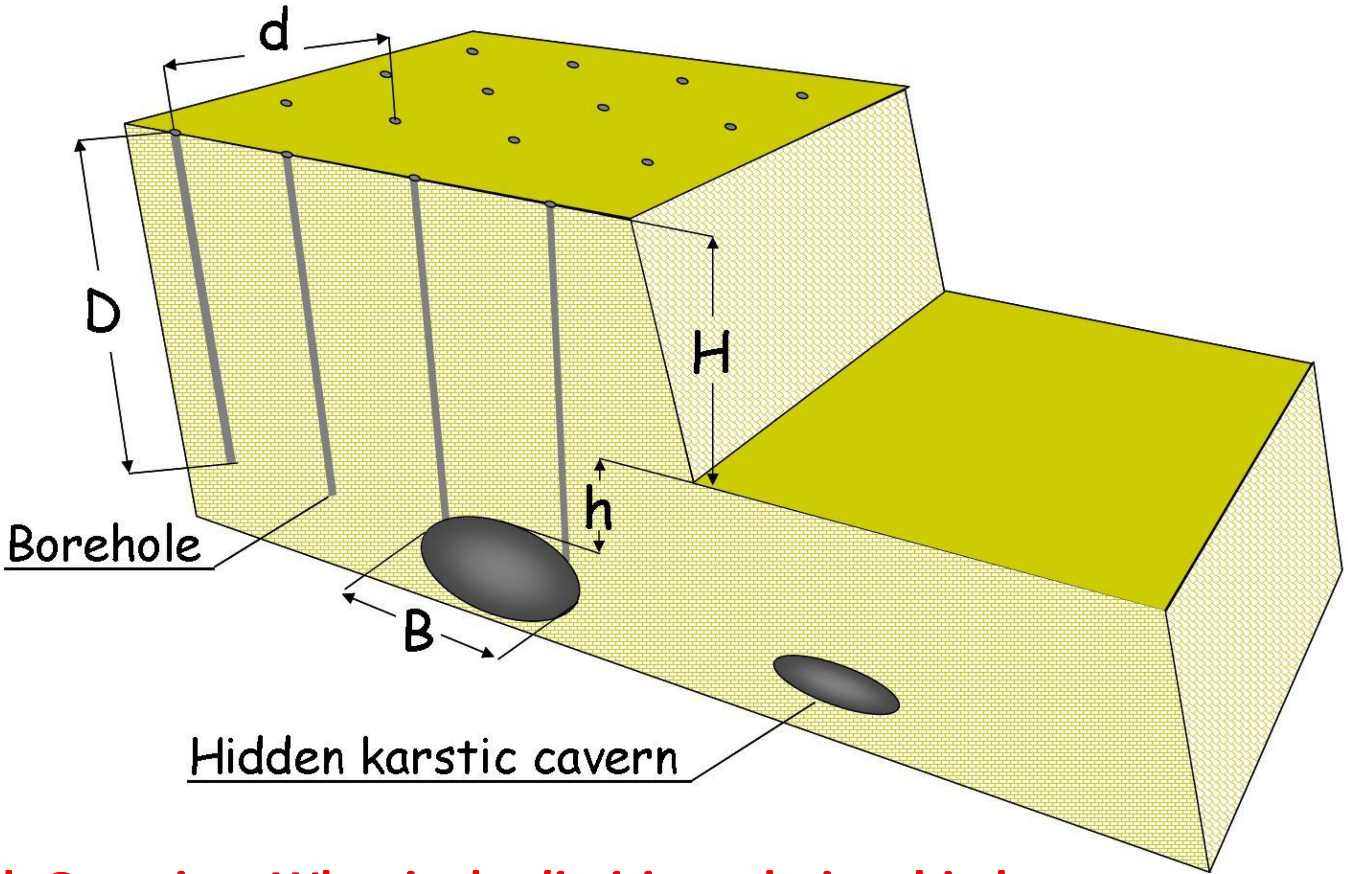
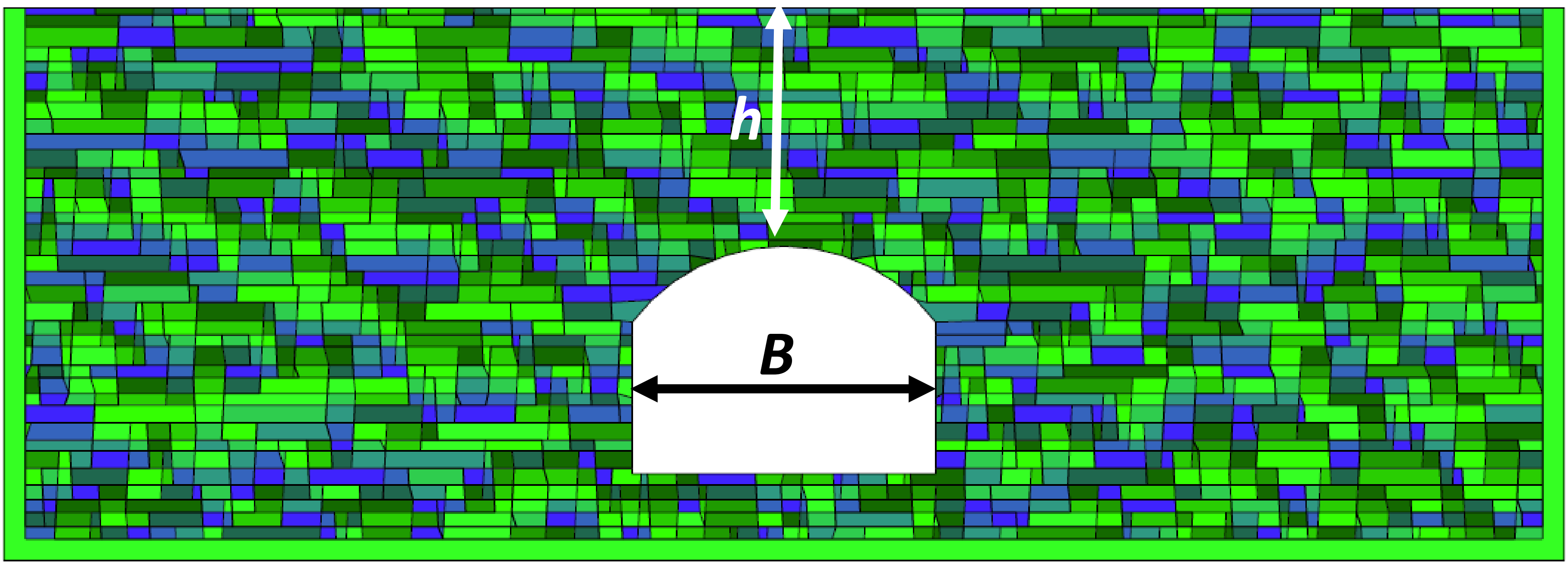
Shallow caverns, typically of *Karstic* origin, may pose great risk to surface civil engineering structures, but are quite difficult to detect, therefore exploration drilling is often employed:



Research Question: What is the *limiting* relationship between cavern span (*B*) and cover height (*h*) that will ensure stability? The answer will constrain the required drilling length (*D*) and distance (*d*) in the exploration effort.

One way to answer this question is to study it numerically with discrete element methods, by generating, synthetically, *Blocky* rock masses and then running forward modeling. Here we keep the rock mass structure constant and change in each simulation the span width (*B*) and cover height (*h*) to obtain the structural response with DDA:



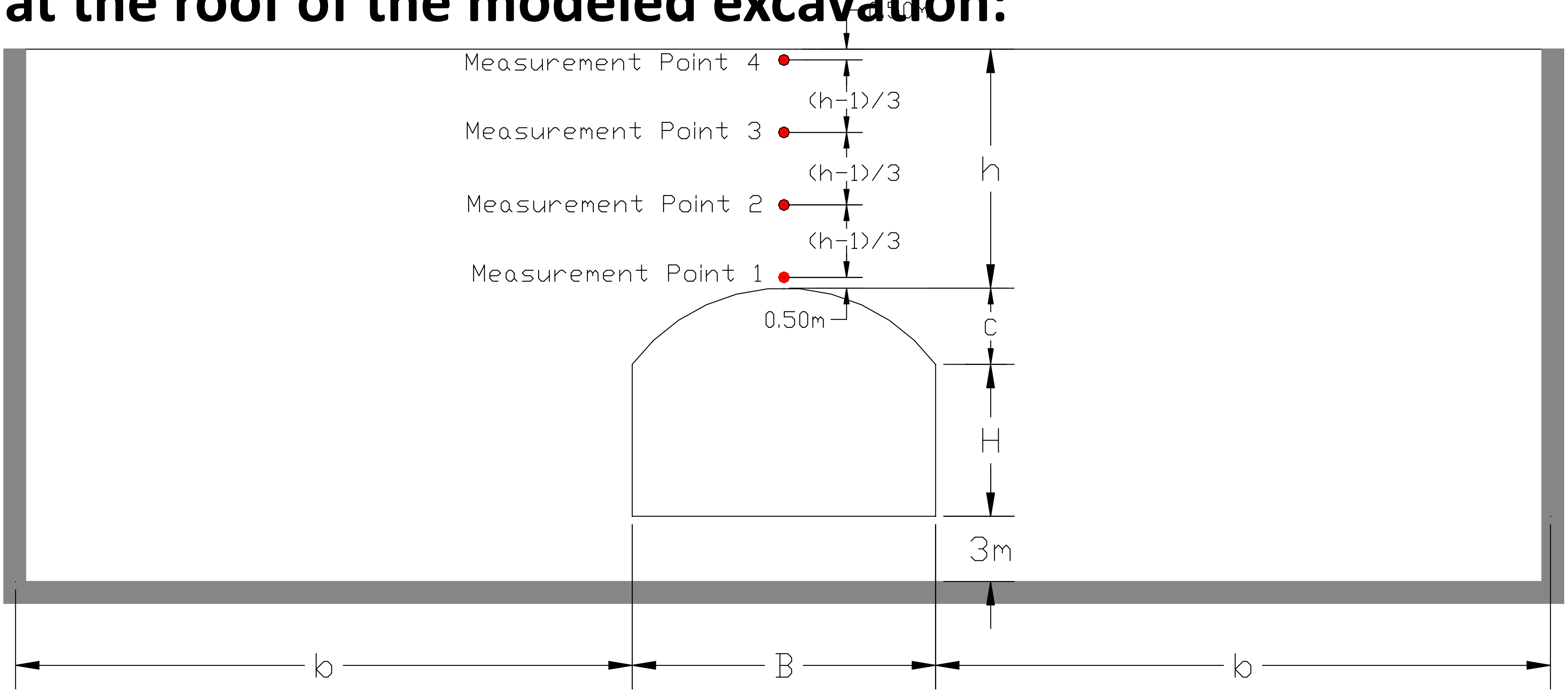
An example of a *blocky* rock mass structure with a synthetic jointing pattern as generated with DDA

The modeled rock mass in our simulations is a ***typical*** blocky rock mass as found in central Israel, with a horizontal bedding planes set and two sub-vertical and sub-orthogonal joint sets:

Joint Set	Dip/Direction	Trace Length	Mean Spacing	Degree of Randomness	Rock Bridge Length
1	0/0	∞	0.70 m	1.0	0 m
2	88/182	5 m	0.96 m	0.5	2.5 m
3	88/102	5 m	0.78 m	0.5	2.5 m

- **These structural parameters represent mean values obtained from a number of joint surveys in central Israel where the problem of karstic cavern collapse exists**
- **The large value of assigned rock bridge length (2.5m) is used to simulate the phenomena of "mechanical layering", where the extent of joint trace length is conditioned by bed thickness**
- **The same effect is obtained by using a relatively small value of trace length (5m) with respect to bed thickness (0.7m).**

To estimate the mechanical stability of each structural configuration, we measure the vertical displacement (*v*) and the horizontal stress (σ_x) components as obtained with forward DDA at four measurement points evenly distributed at the roof of the modeled excavation:

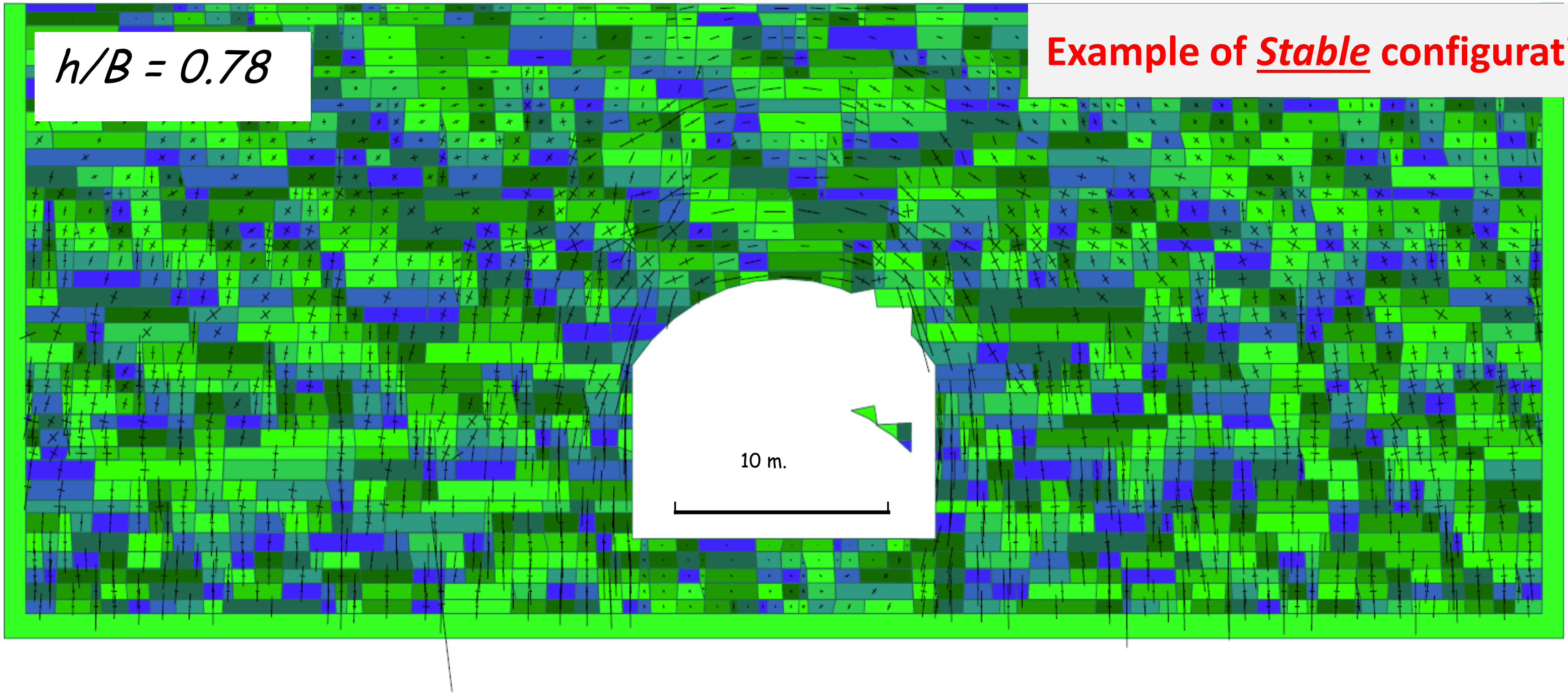


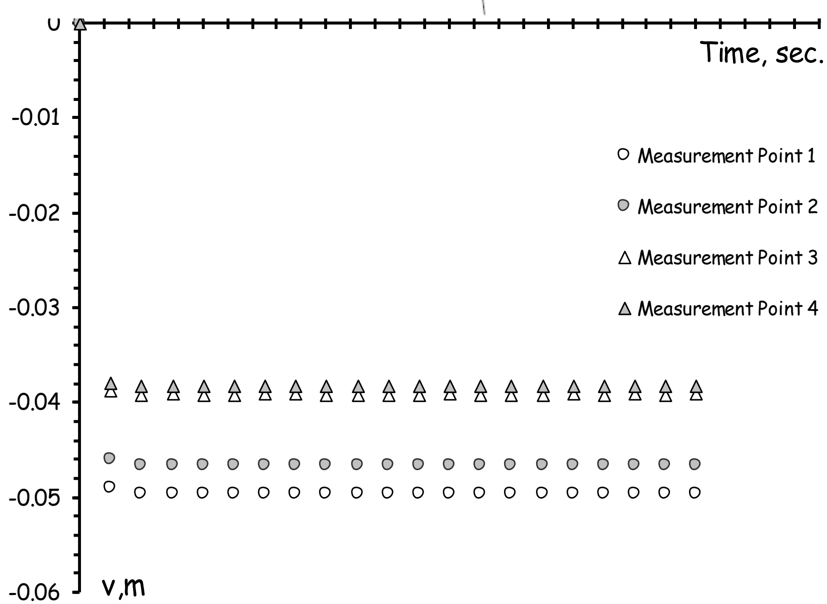
The lateral boundaries are set at a distance of *b* = 3*B* to ensure the decay of stress concentrations near the boundaries of the modeled domain.

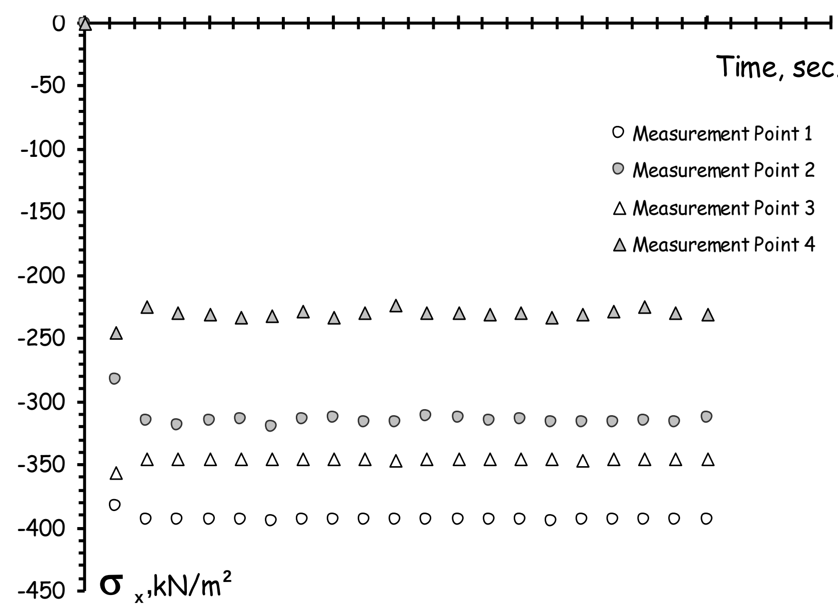
The results of forward modeling with DDA are classified into three categories of structural response, depending on the vertical displacement (*v*) and horizontal stress (σ_x) component outputs at the measurement point locations:

- ***Stable*** **Configuration: the 3 upper measurement points exhibit static stability**
- ***Marginally Stable*****: the 2 upper measurement points exhibit static stability**
- ***Unstable*****: Only the upper measurement point or no measurement point exhibit static stability**

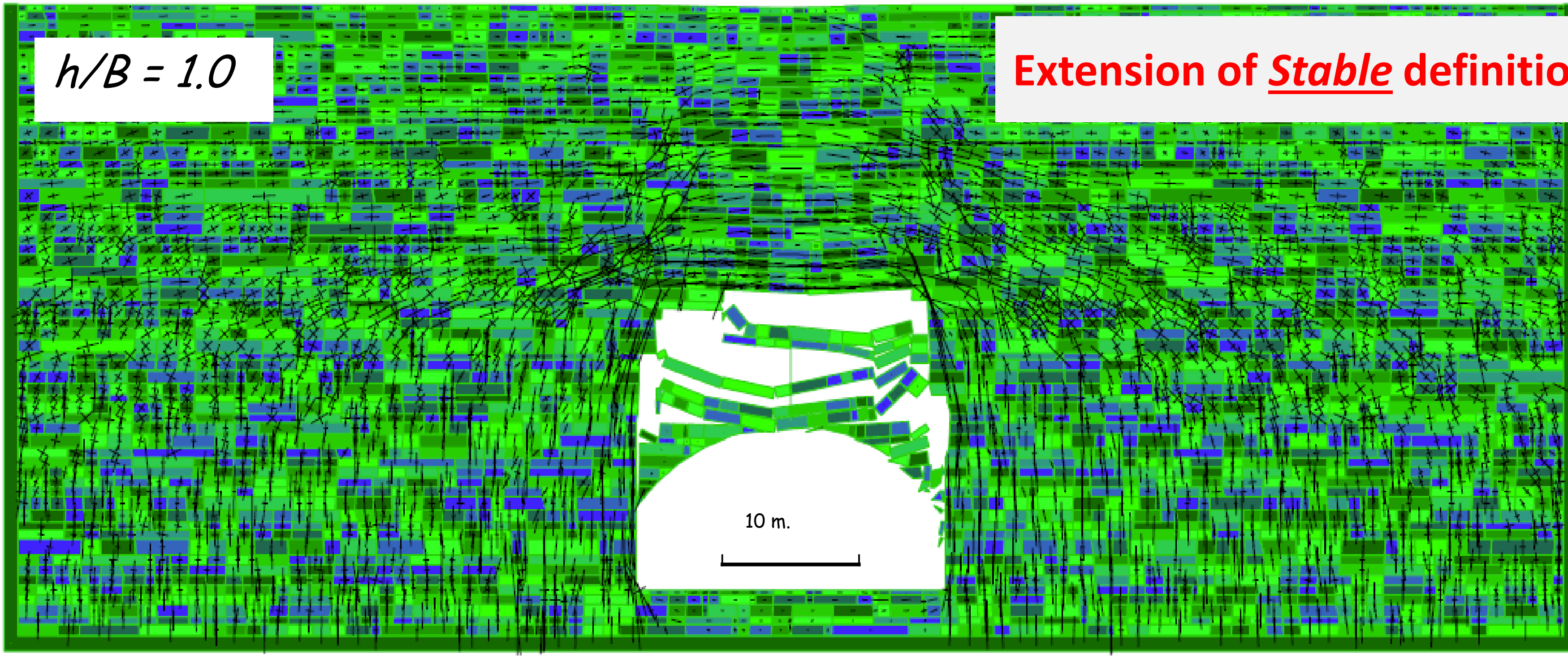
Example of *Stable* configuration

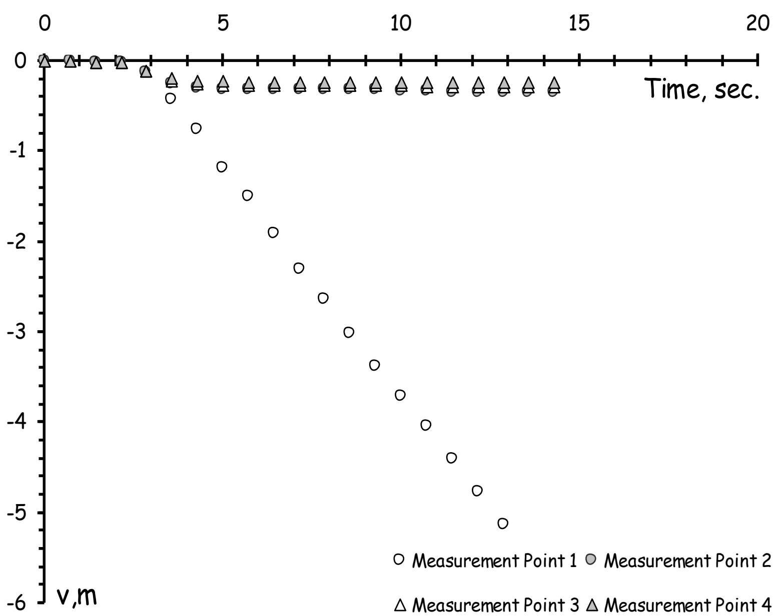


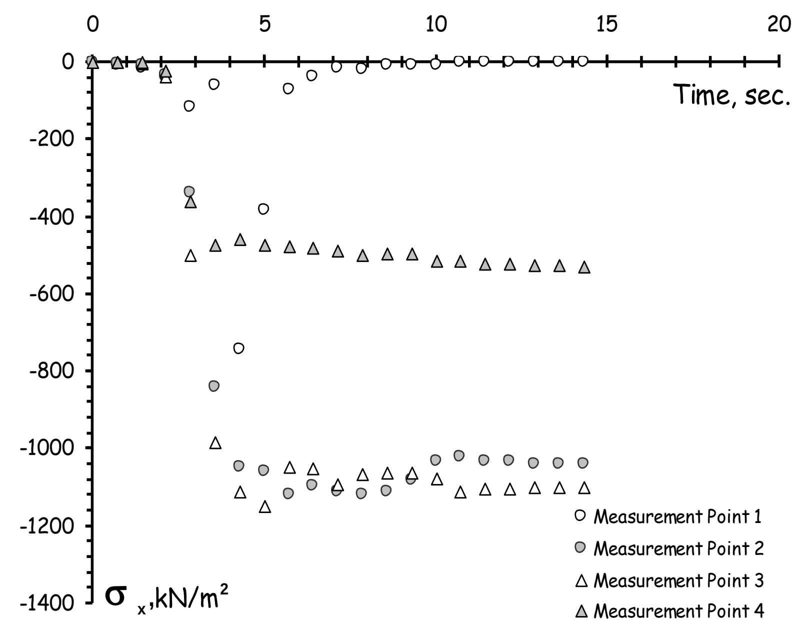




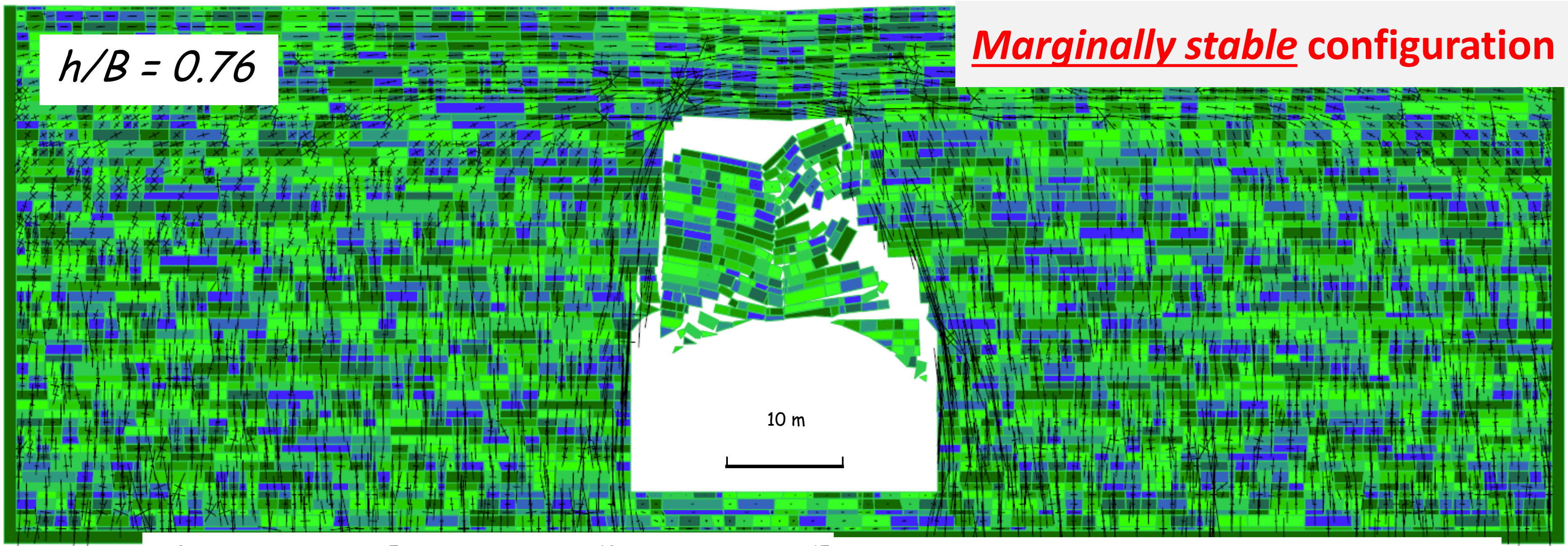
Extension of ***Stable*** definition

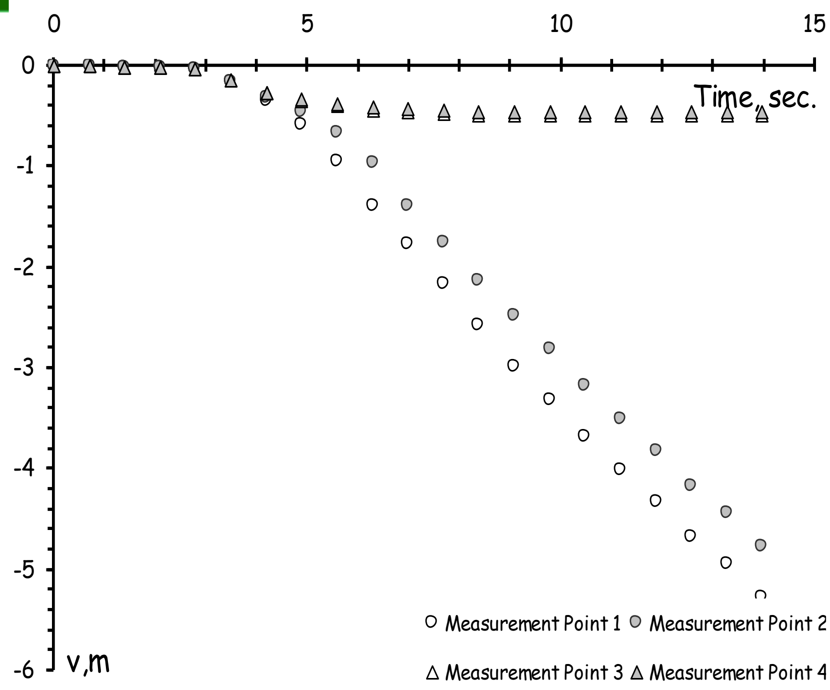


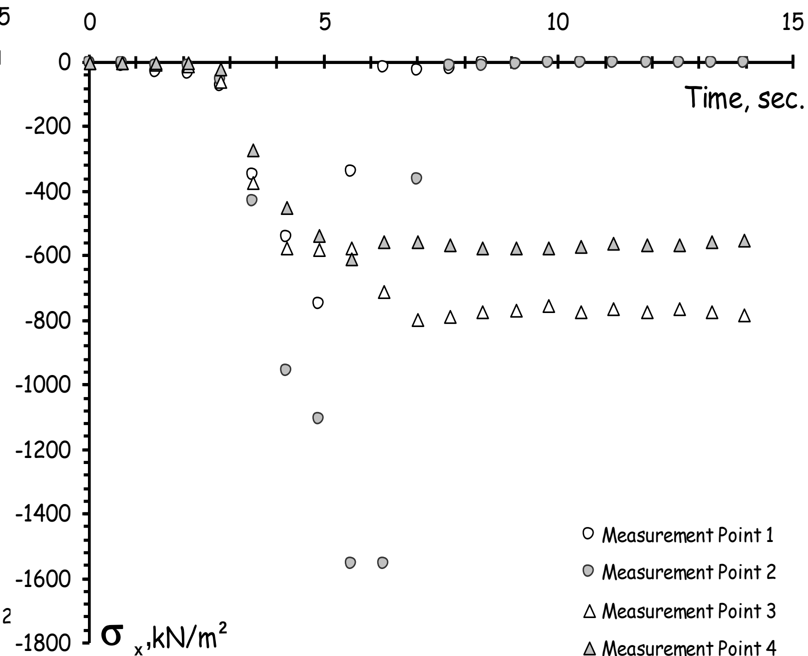




Marginally stable configuration

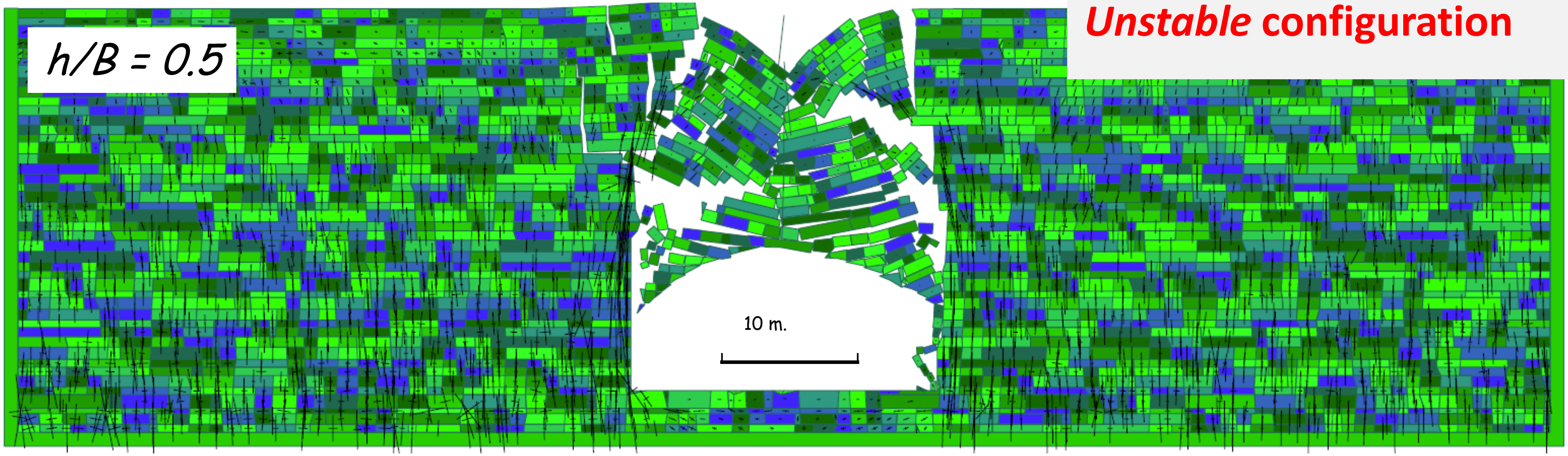


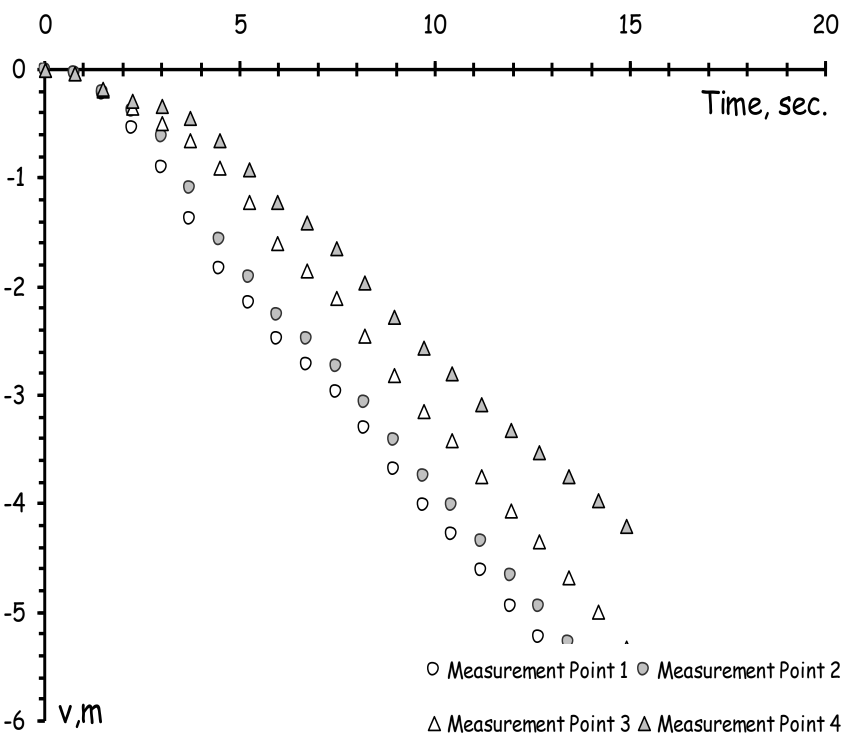


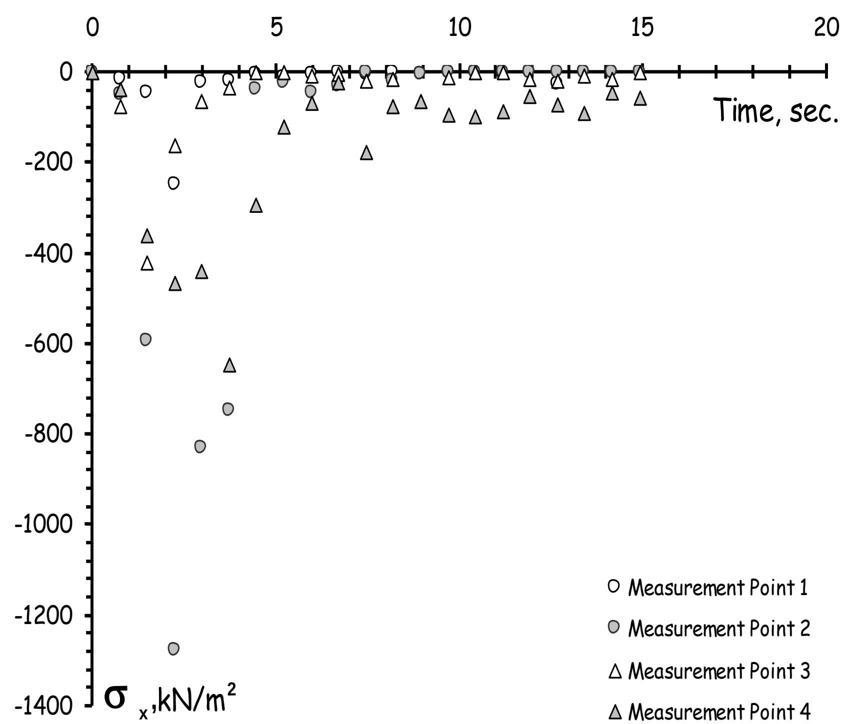


B

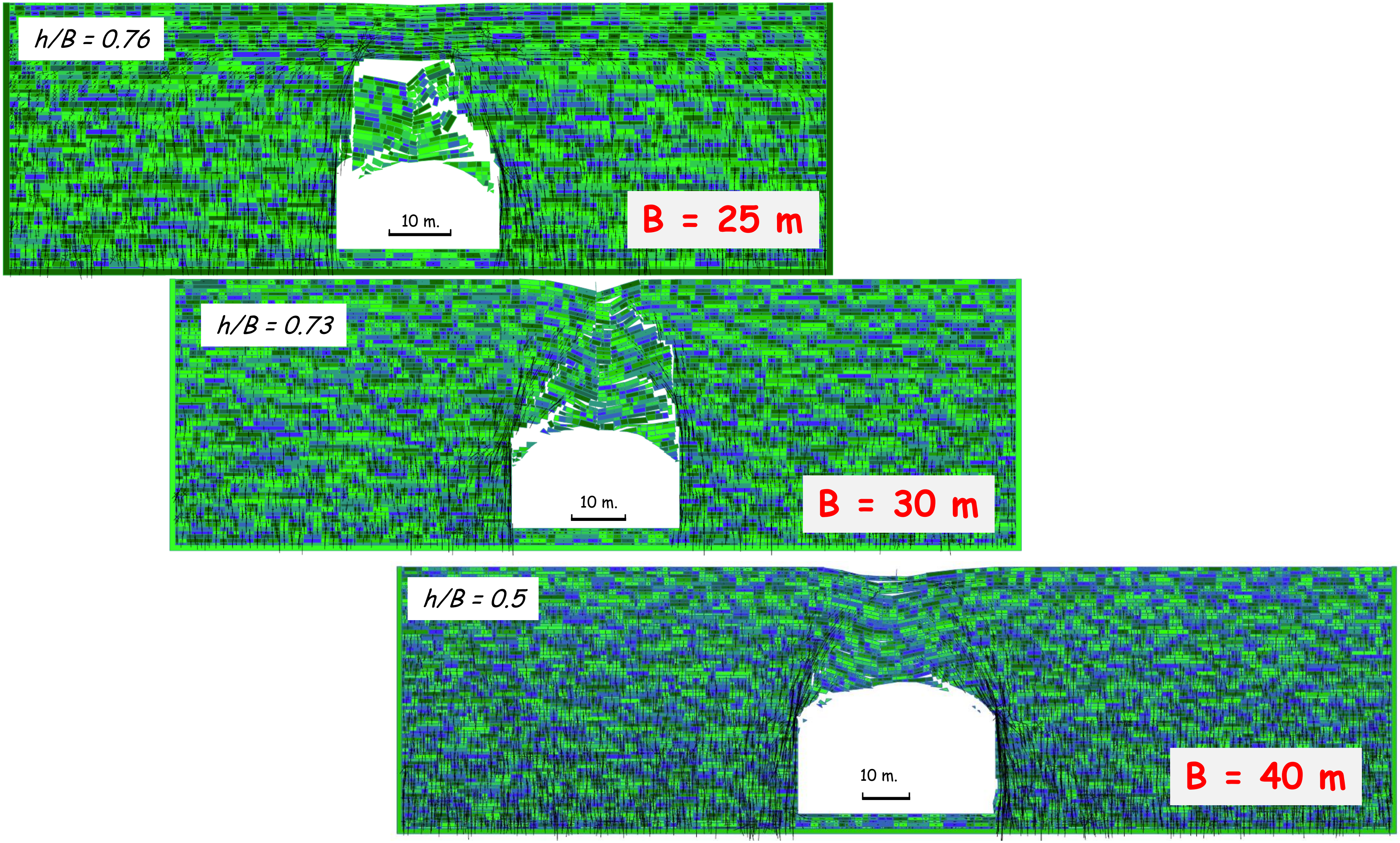
Unstable configuration



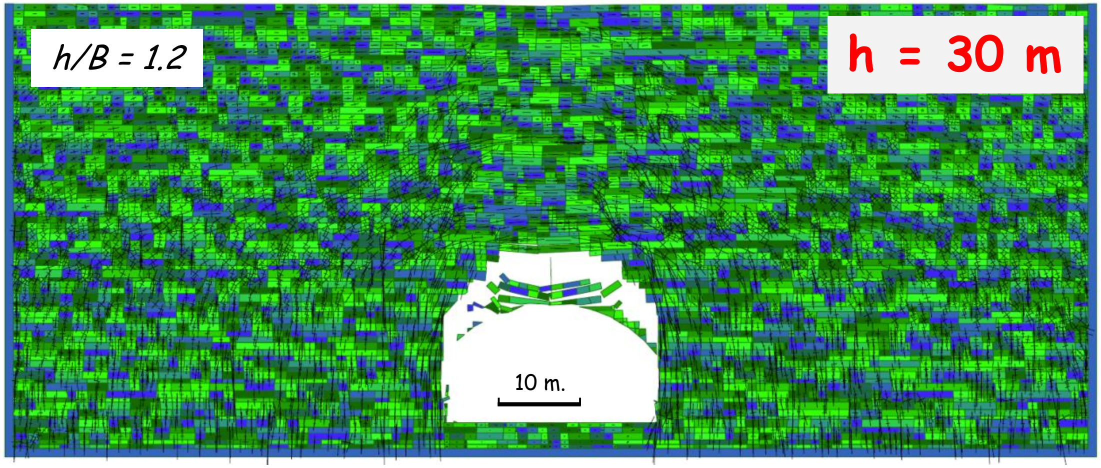


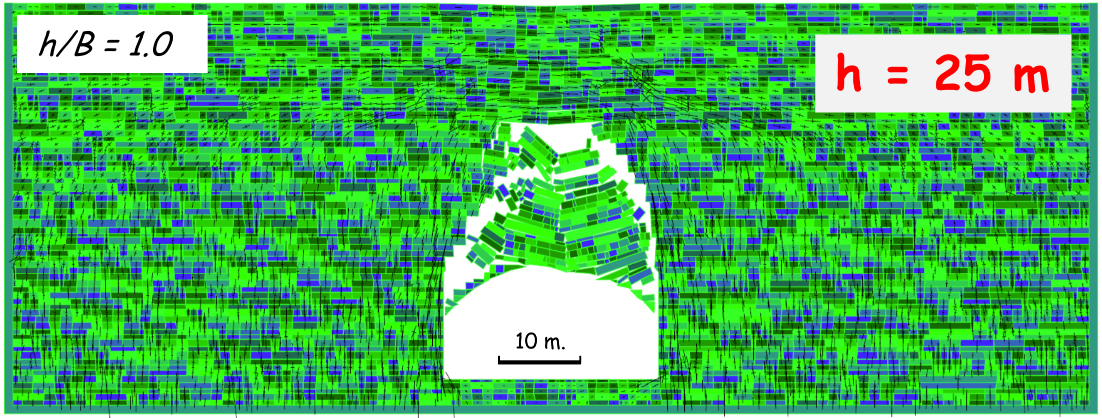


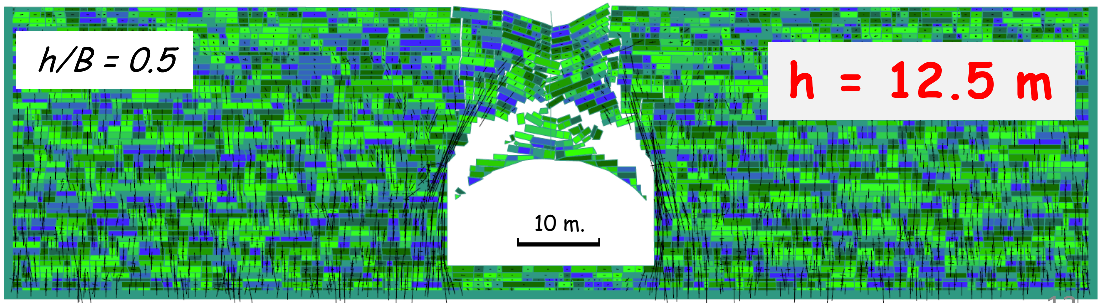
As we know, per a given cover height (here *h* ~ 20 m) the span width adversely affects stability:



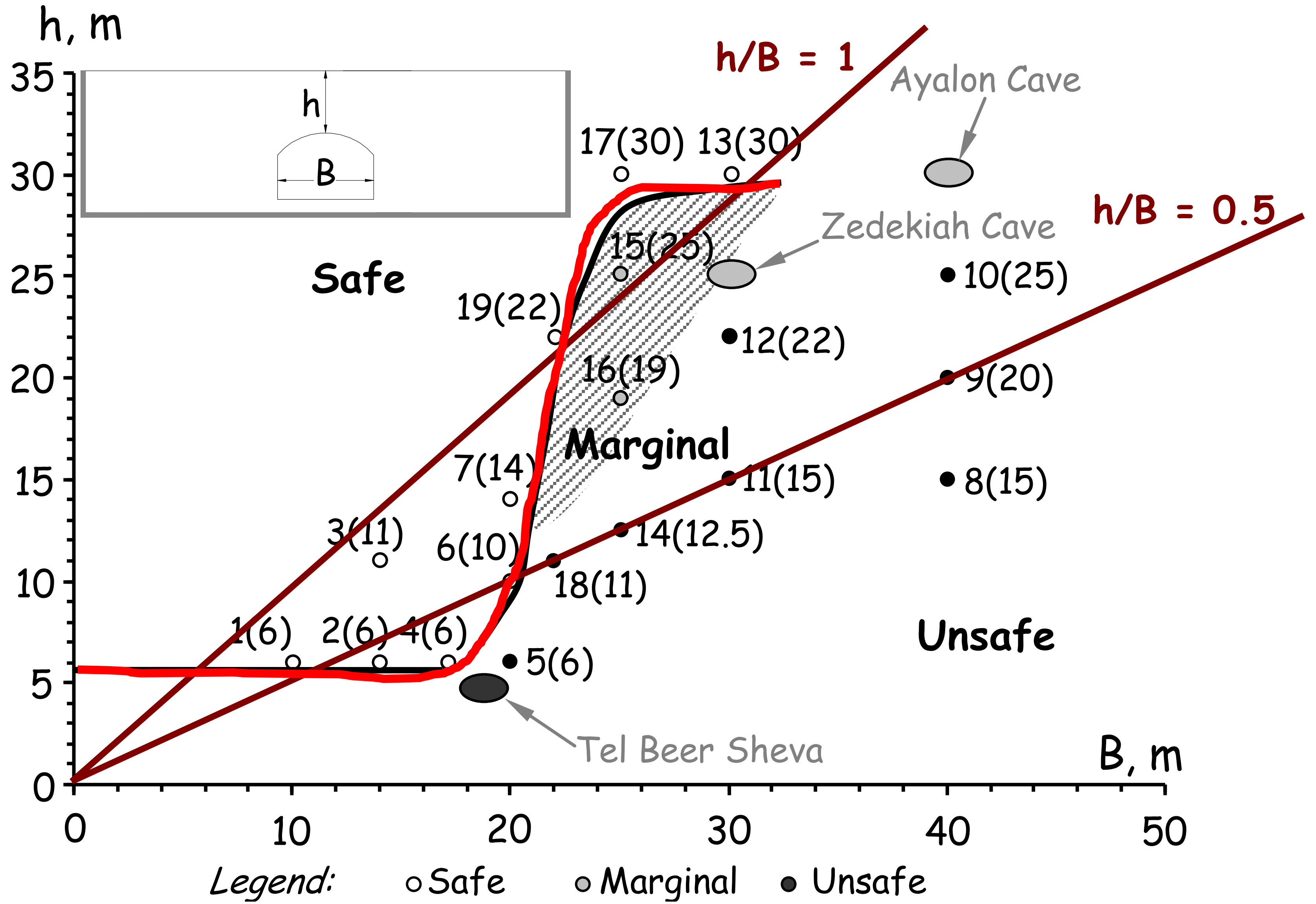
Similarly, per given cavern span (here *B* = 25 m) the cover height positively affects stability:







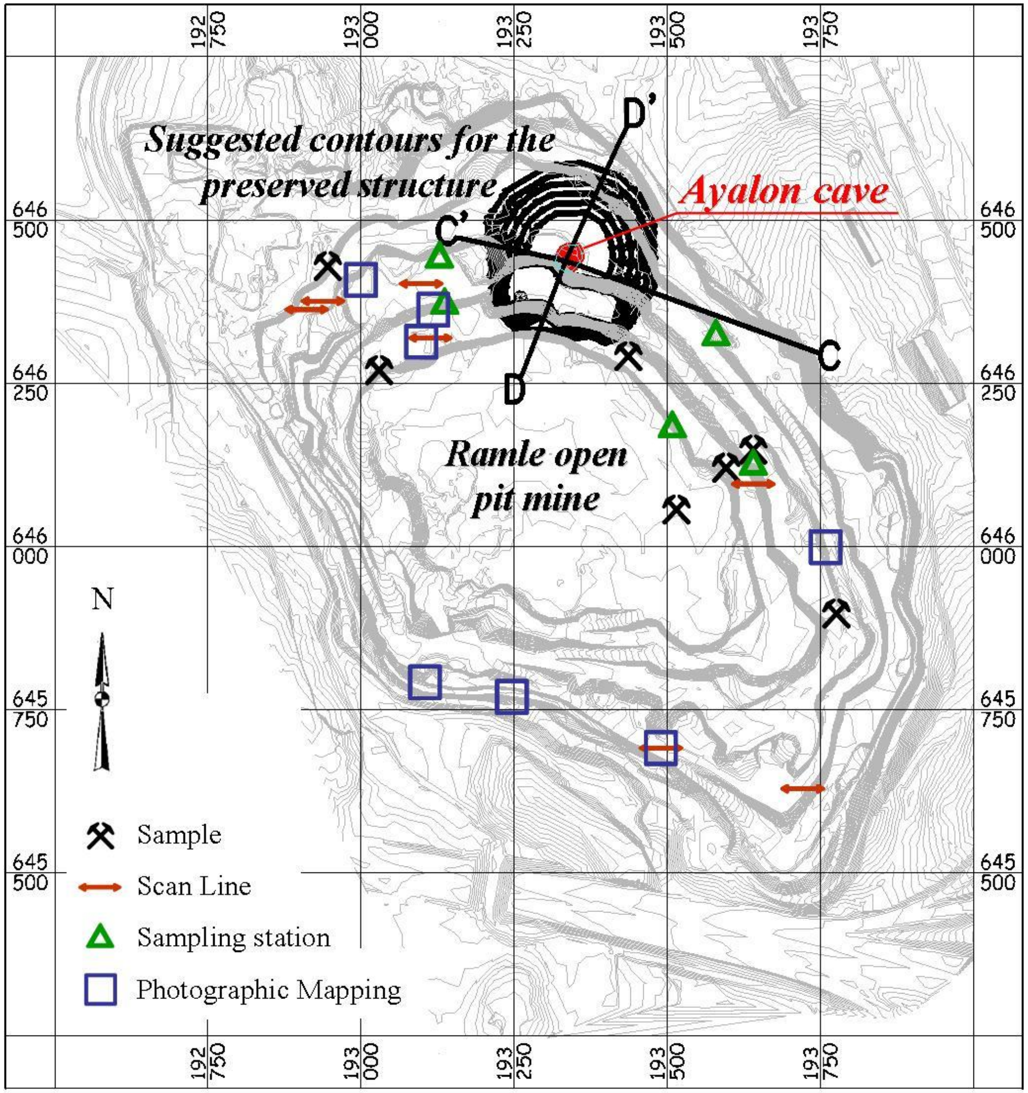
The final resulting relationship between *B* and *h* required for stability however proves to be *not* linear:



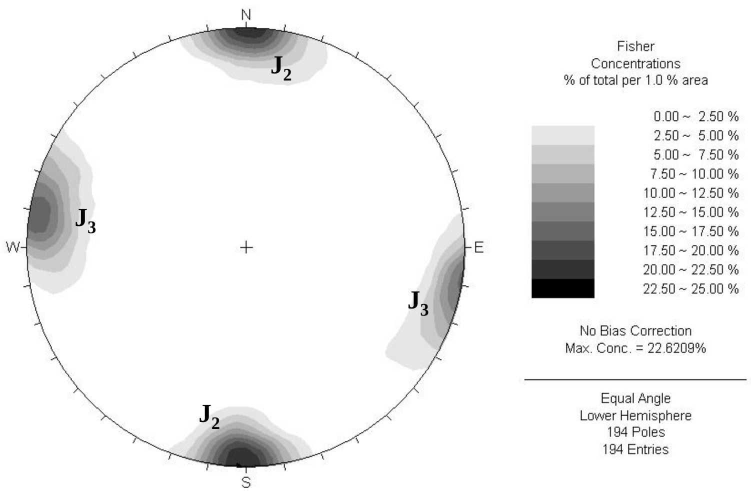
The above was shown for the same, synthetically generated, rock mass structure. Results from three different case studies in different rock masses support our concluding chart:

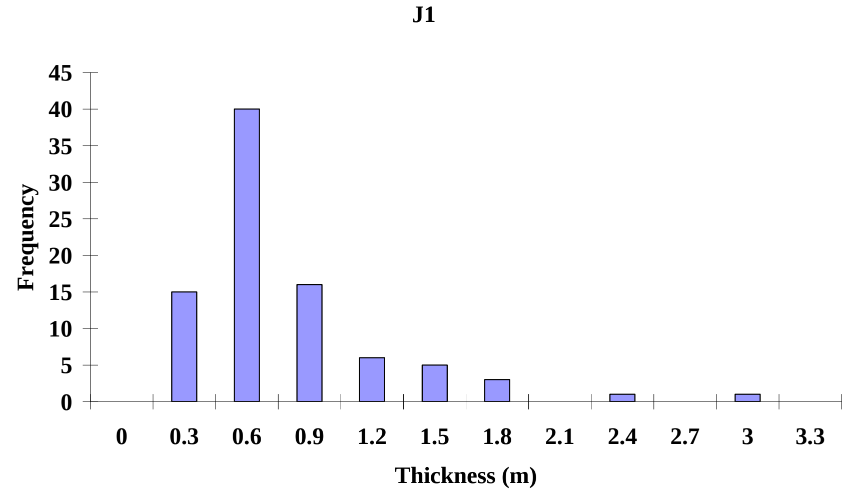
1. **The *Ayalon* cave underneath Ramle open pit mine – central Israel**
2. **The 2000 year old *Zedekiah* quarry - underneath the old city of Jerusalem**
3. **The Tel Beer Sheva 3000 year old underground water storage system – southern Israel.**

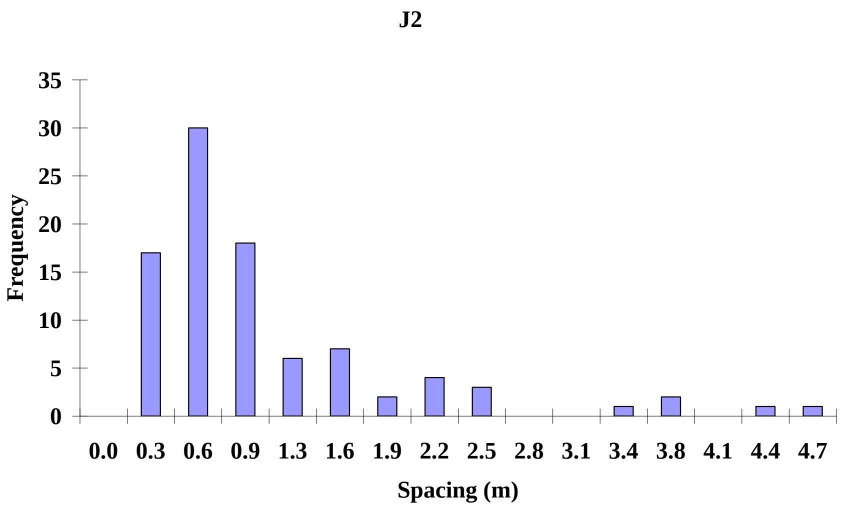
Case 1: *Ayalon Cave* – a present day 40 meter span karstic cavern underneath an active open pit mine with 30 meters of rock cover:

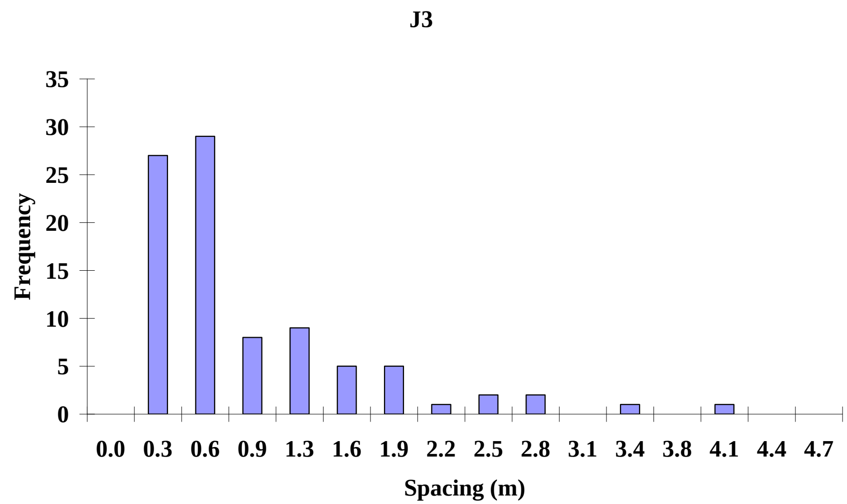


Statistical joint survey results:

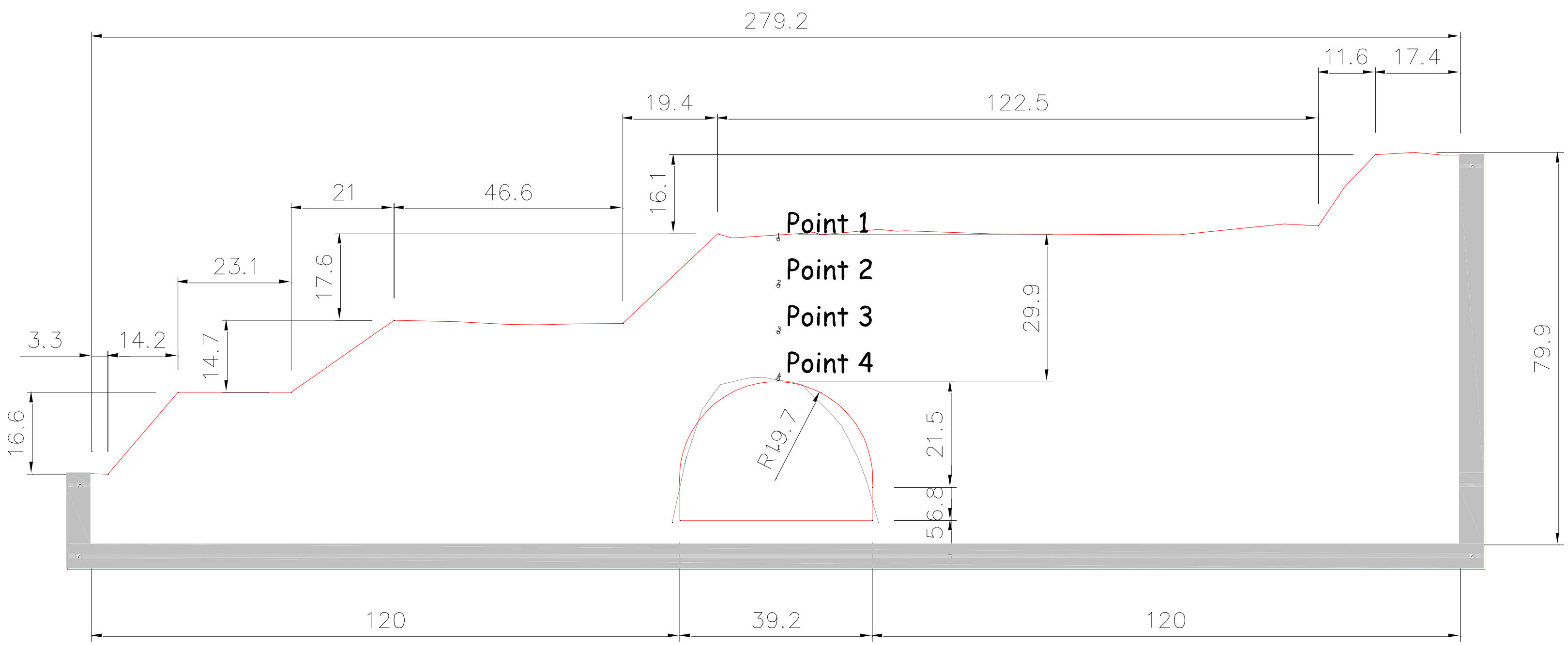




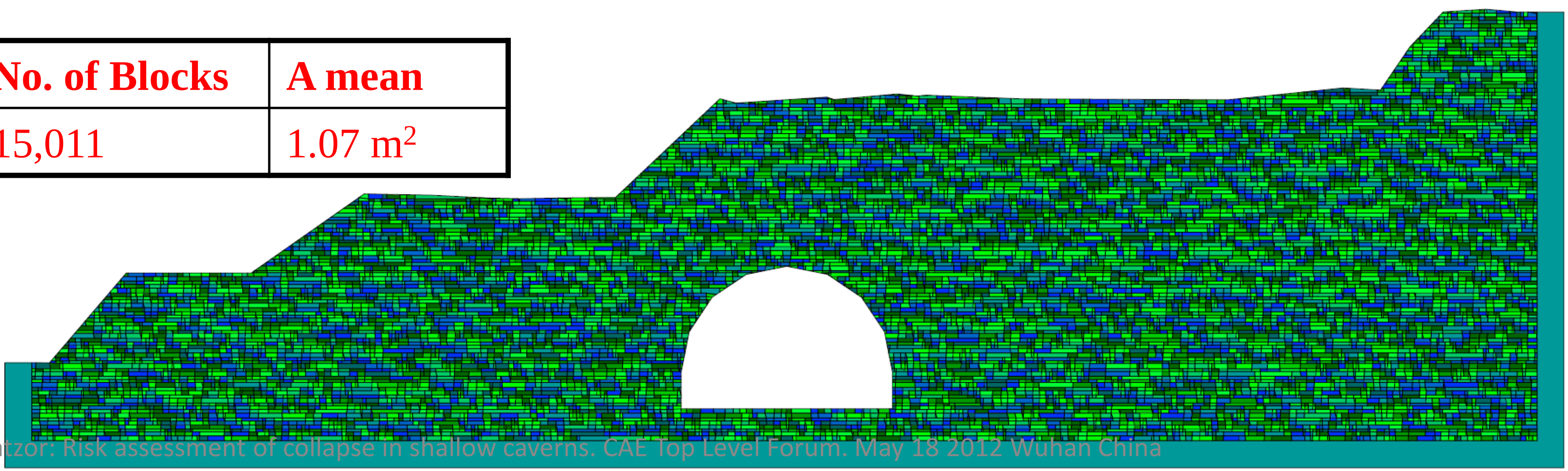




Current configuration of explored cavern underneath the mine:

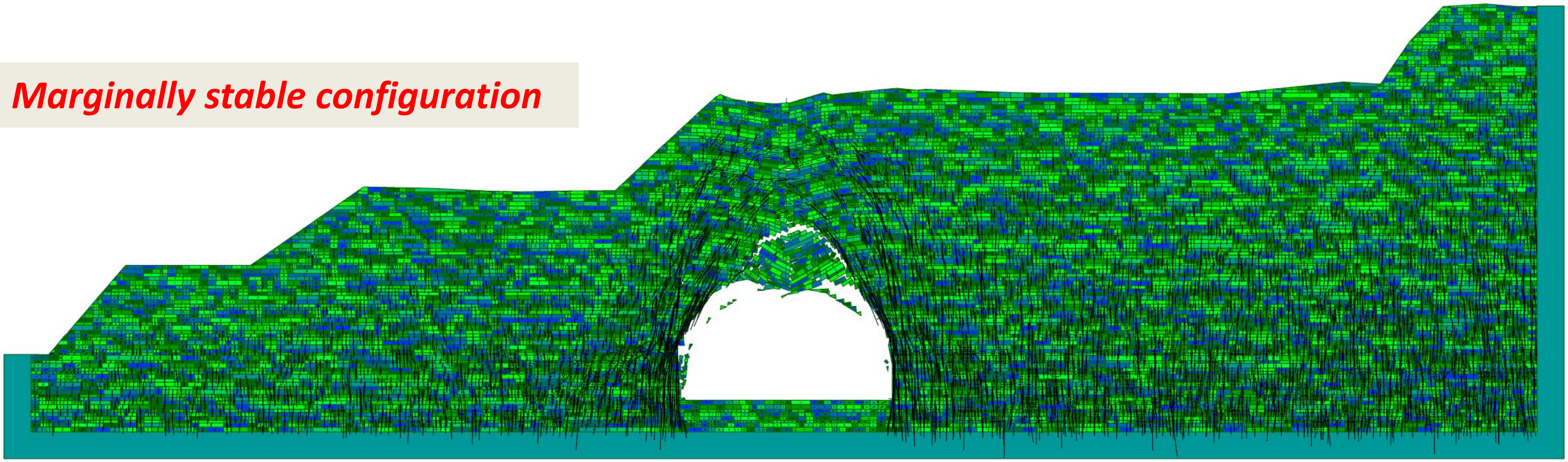


No. of Blocks	A mean
15,011	1.07 m^2

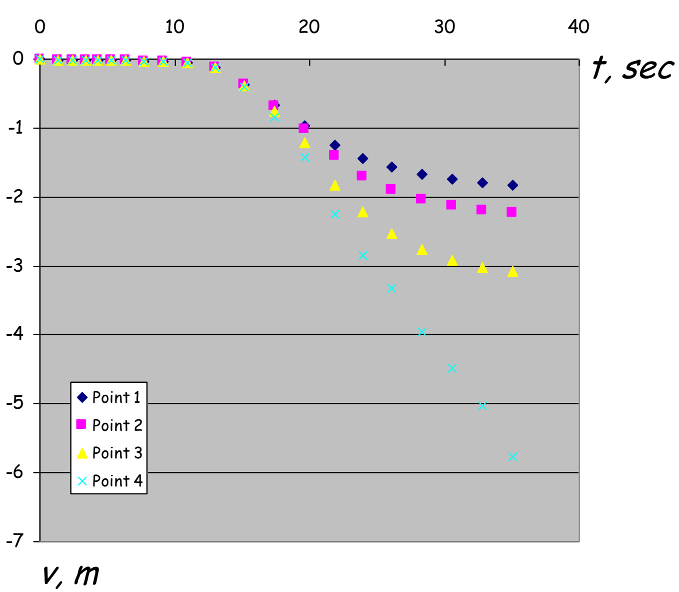


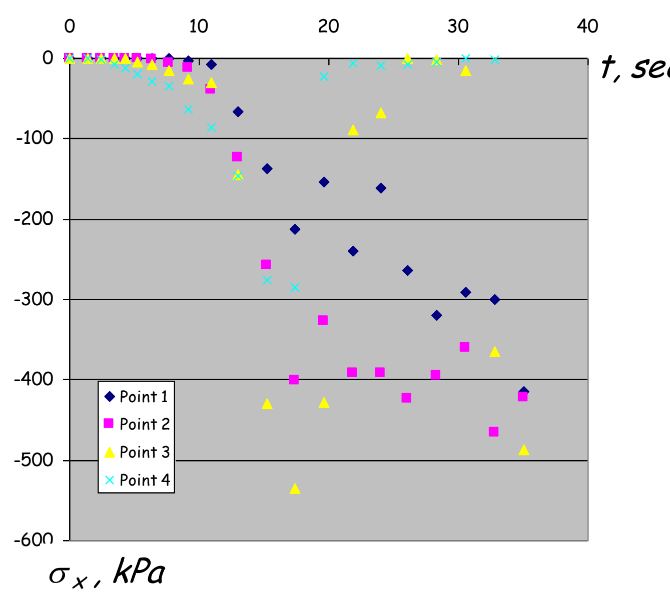
Results of forward analysis with DDA:

Marginally stable configuration

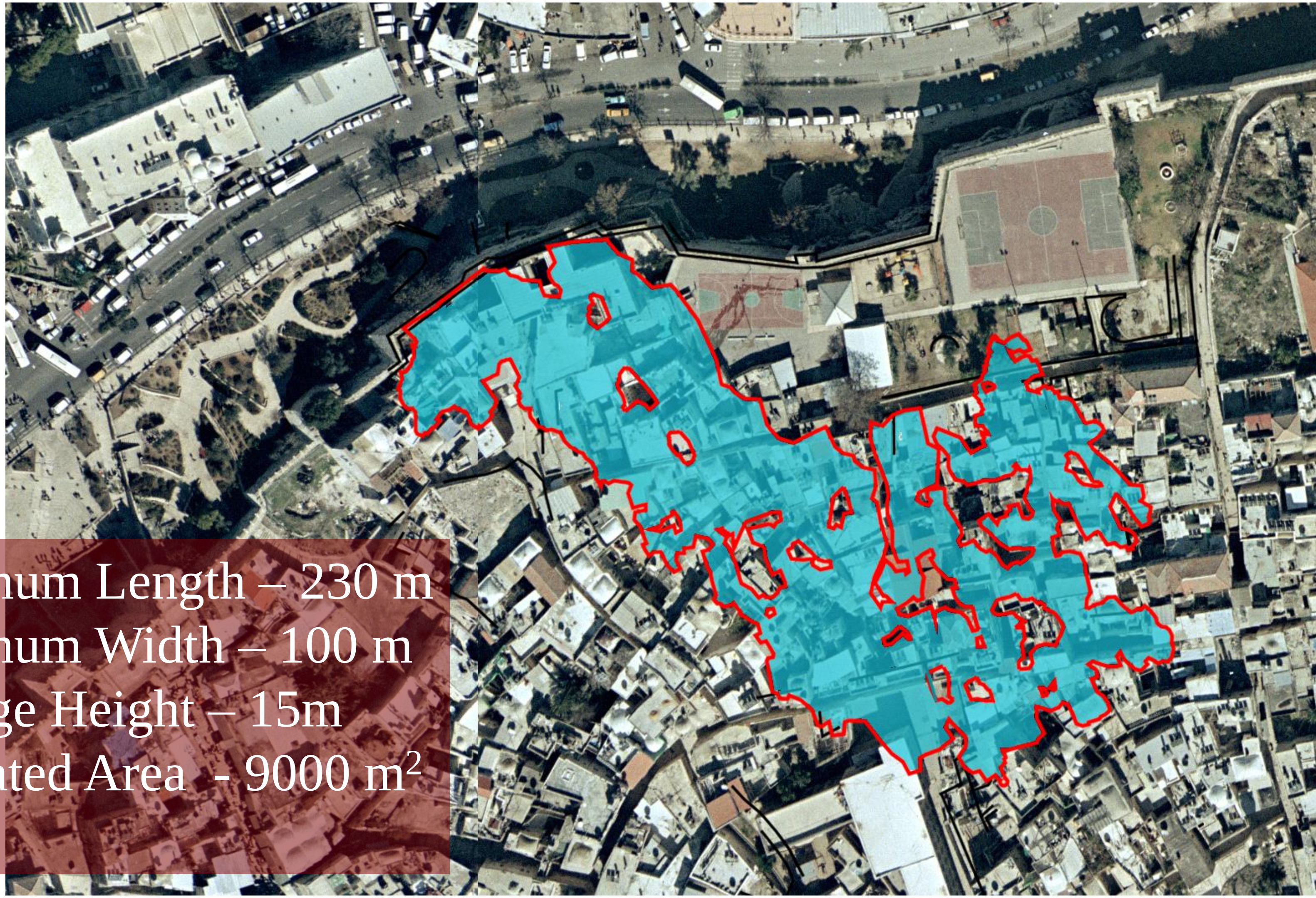


No. time steps	90,000
Real Time	35.04 s
Mean no. it. pts.	5.26
CPU time	361 hr.



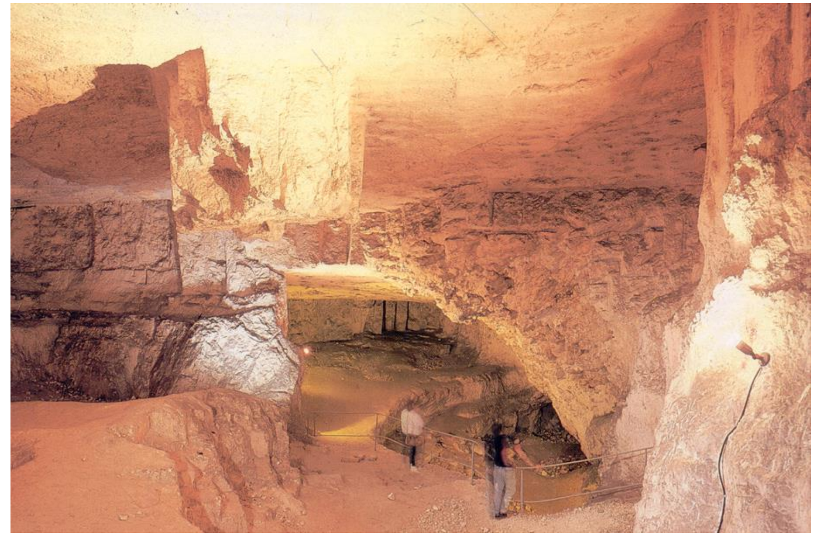


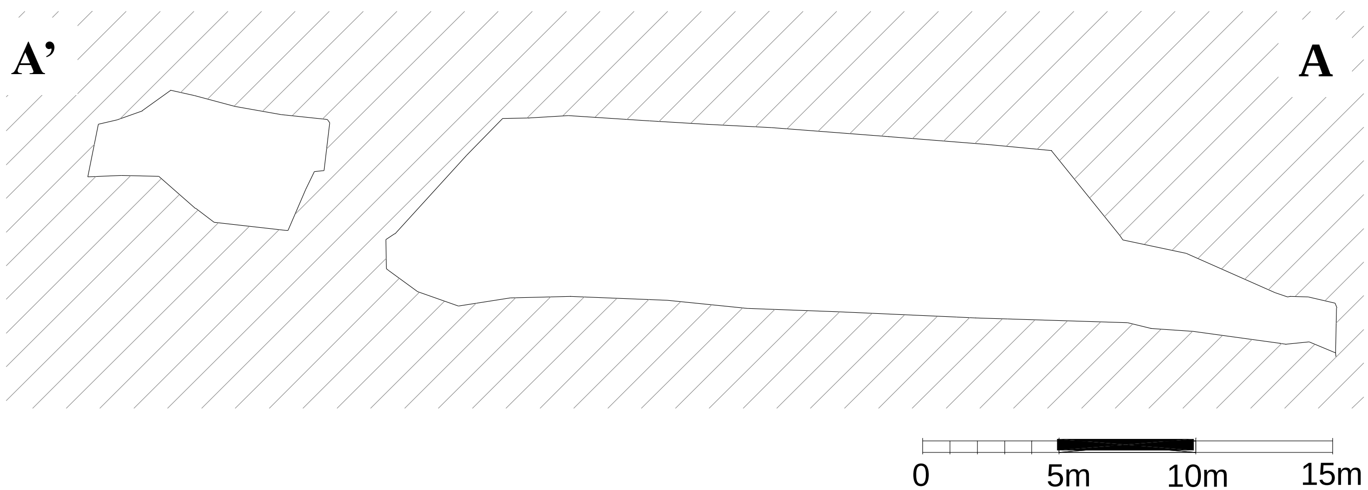
Case 2: *Zedekiah cave* – a 2000 years old 30 meter span cavern with 25 meter cover under the old city of Jerusalem:



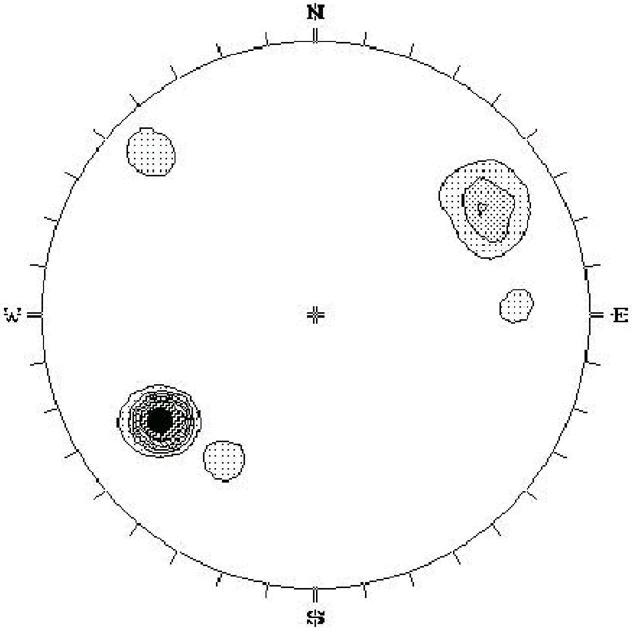
Maximum Length – 230 m
Maximum Width – 100 m
Average Height – 15m
Estimated Area - 9000 m^2

Cross section through main chamber





Rock Mass Structures

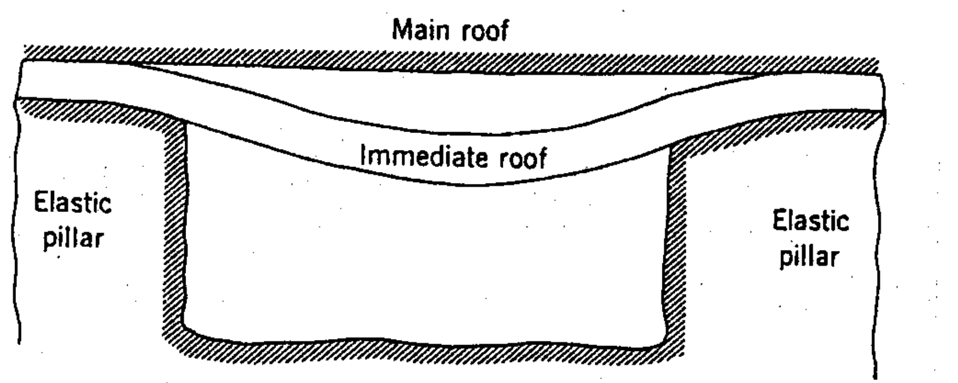


Set	Type	Dip	Spacing
1	Bedding	08/091	0.85
2	Shears	71/061	0.79
3	Shears	67/231	1.48
4	Joints	75/155	1.39

Roof stability assuming bedding planes only

Free span (L)	30 m
Beam thickness (t)	0.85 m
Unit weight (γ)	19.8 kN/m^3
Elastic modulus (E')	8*10^3 MPa
Uniaxial compressive strength (σ_c)	16.4 MPa (bedding parallel)
Tensile strength (σ_t)	2.8 MPa

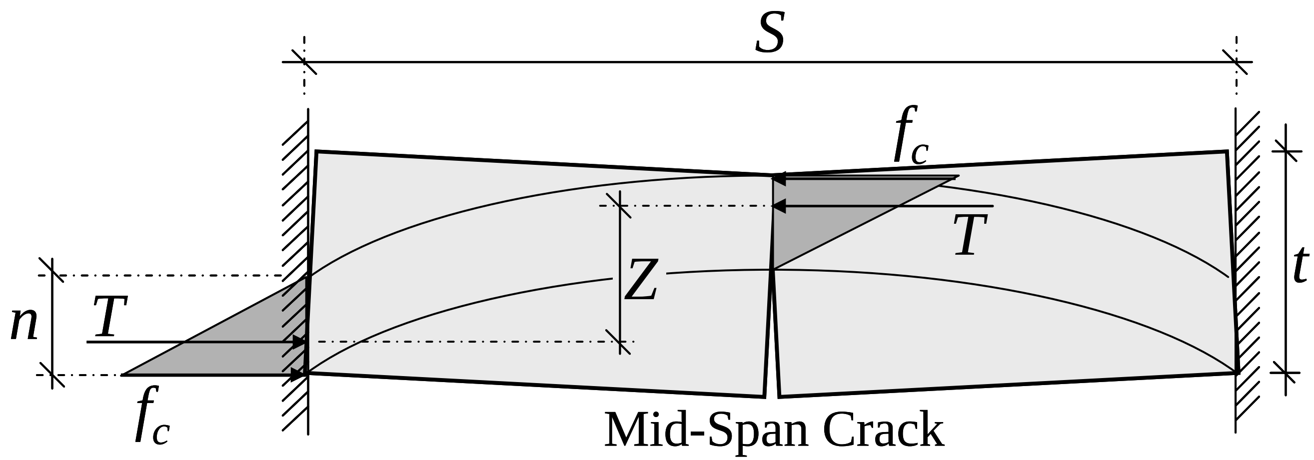
Maximum deflection at centerline (η)	8.67 cm
Maximum shear stress at abutments (τ_{max})	0.445 MPa
Maximum axial stress (σ)	10.5 MPa



The roof should have failed in tension…

Roof stability assuming the Voussoir analogue

Since the tensile strength of the material is exceeded in at the lowermost layers of the roof a vertical crack may propagate and decompose the continuous roof slab into two blocks, thus forming the so called "Voussoir Bean" (See Ray Sterling PhD thesis and Brady and Brown, 2004):

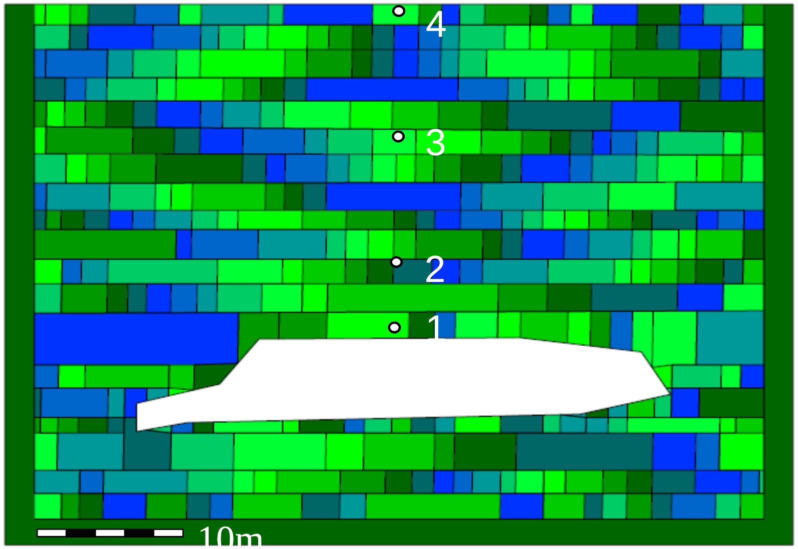


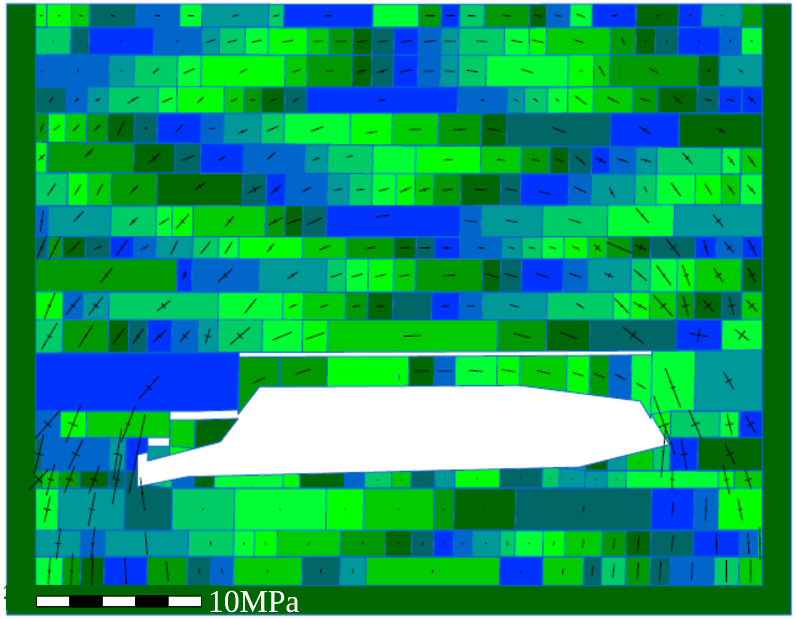
With the given dimensions the roof should undergo buckling culminating in a "snap – through" mechanics (Z < 0).

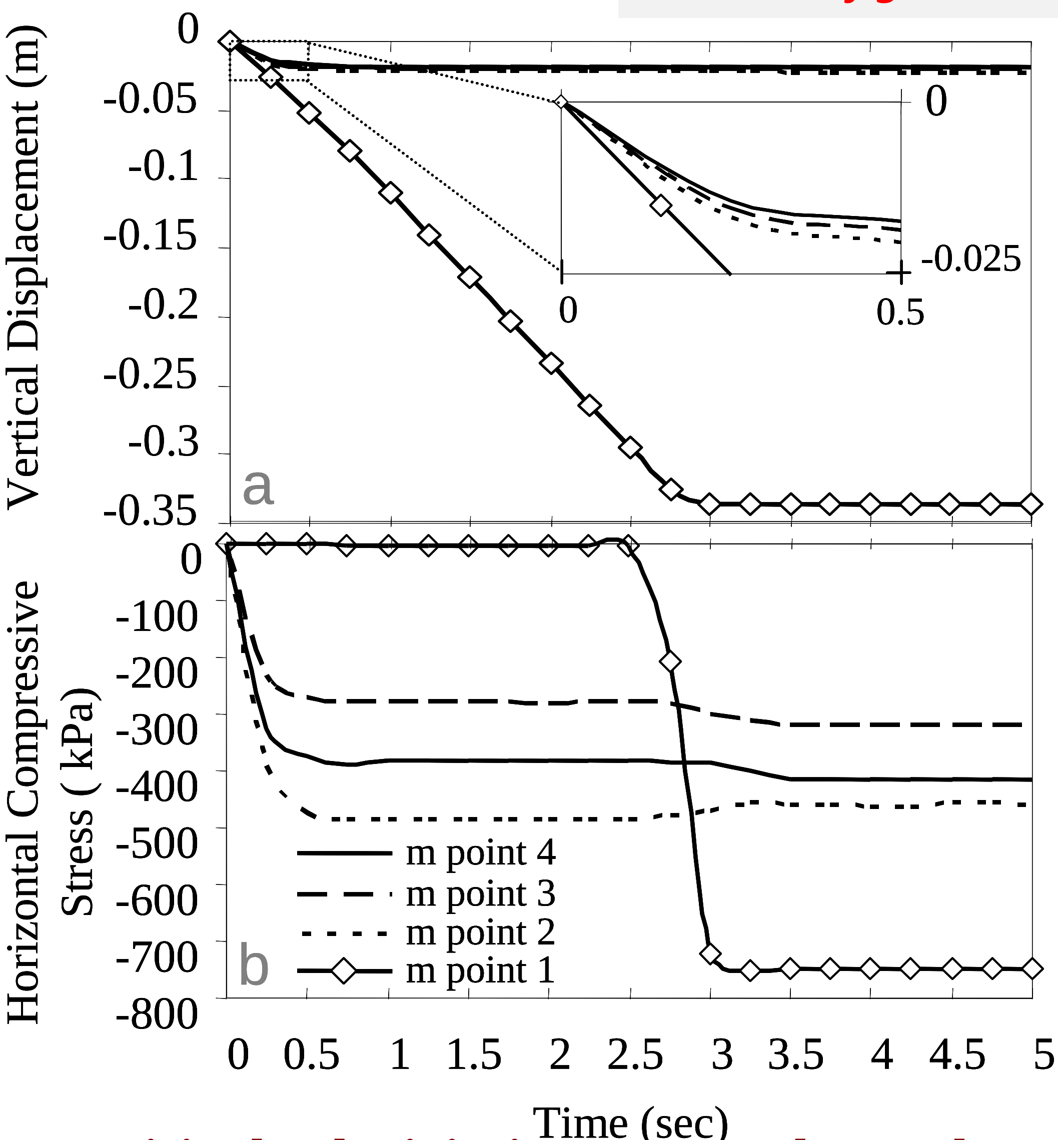
So, what is keeping the roof stable?...

Results of forward modeling with DDA:

Stable Configuration

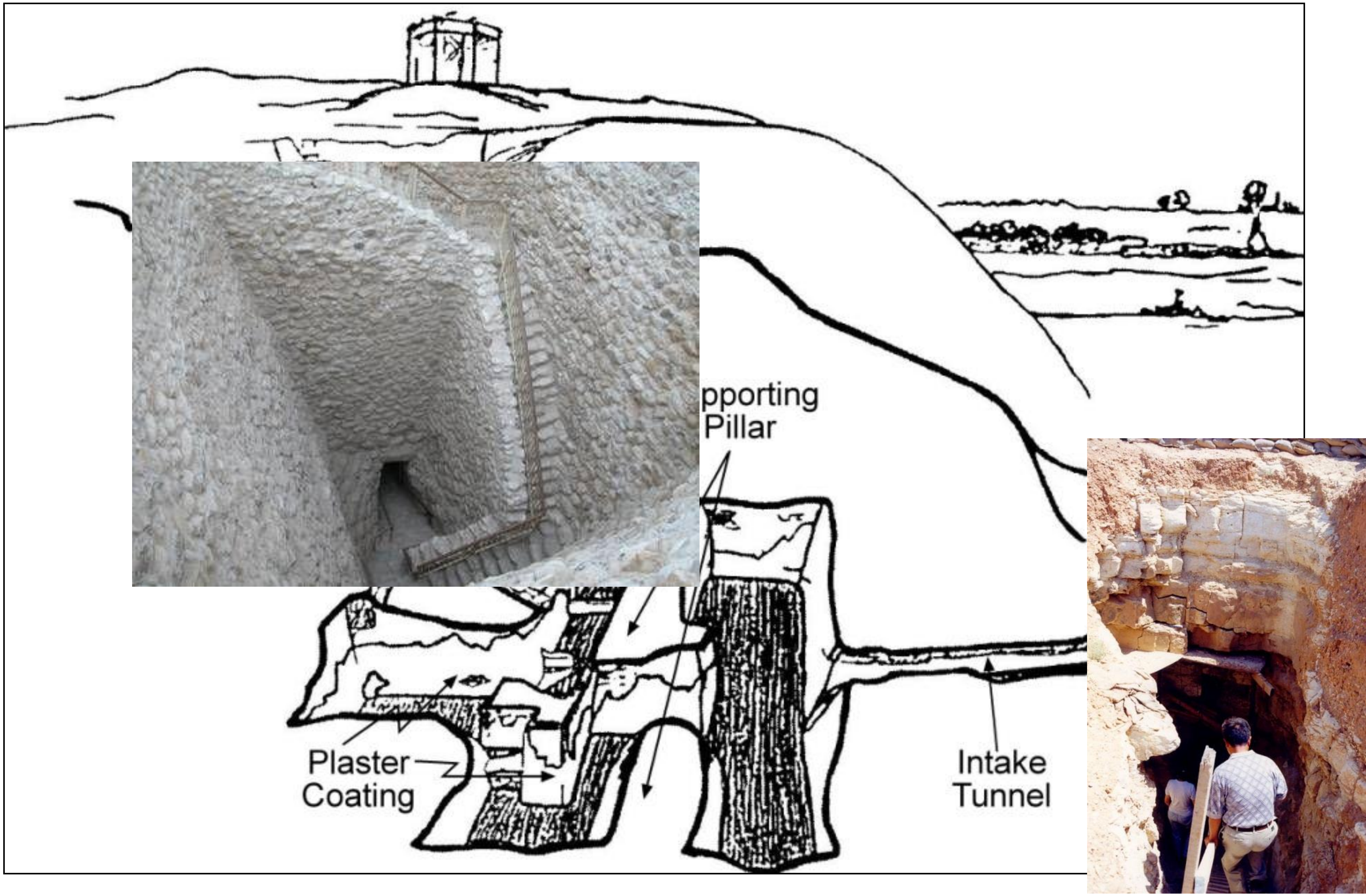




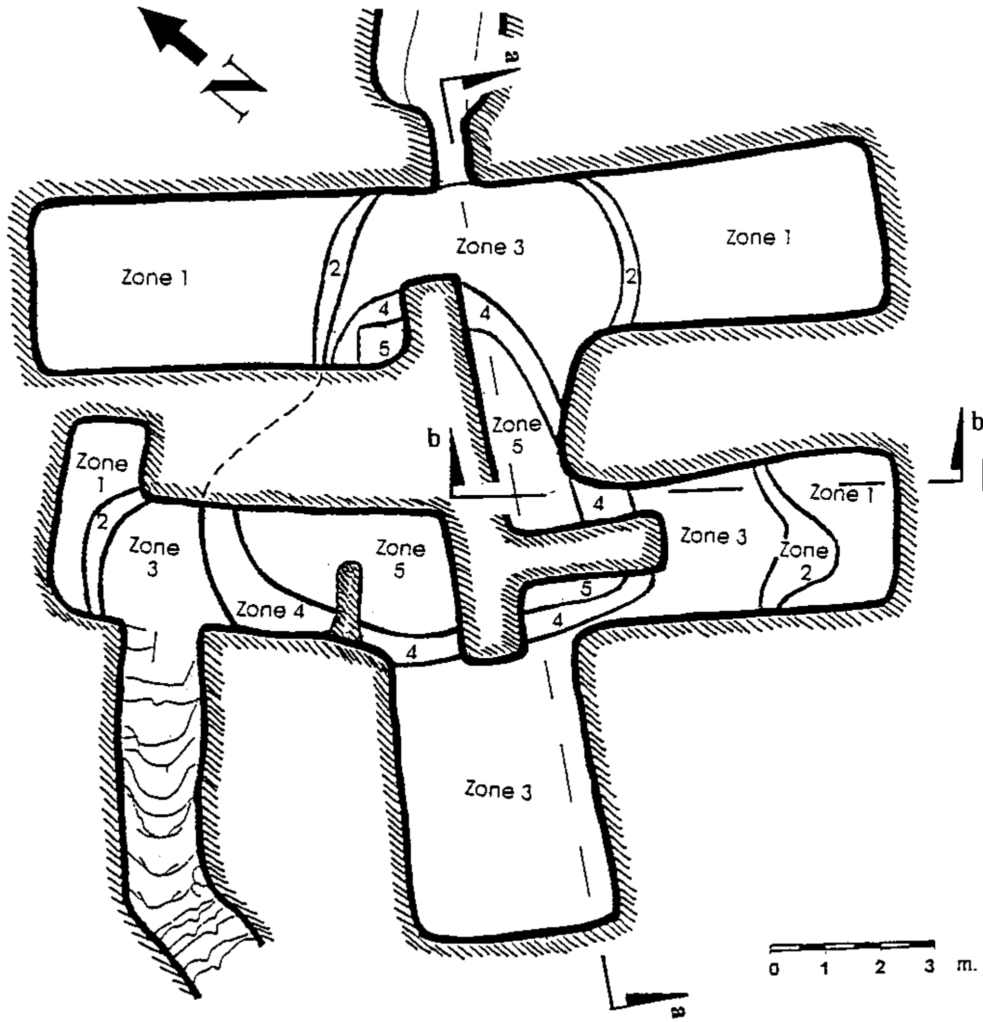


Surprisingly, the jointing patterns keeps the roof stable…

Case 3: Tel Beer-Sheva – a 3000 years old underground water storage system

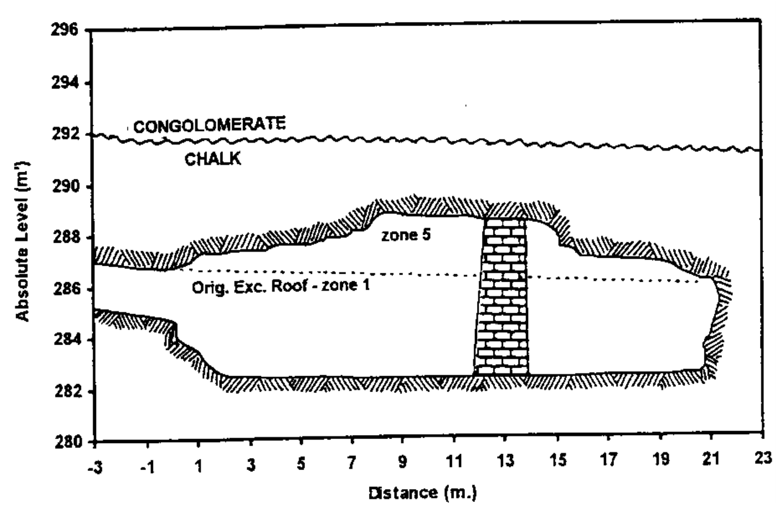


Underground System Layout:



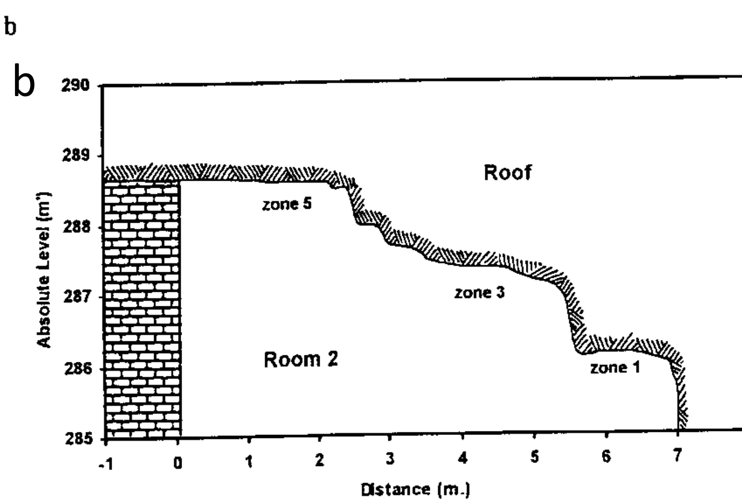
a

a



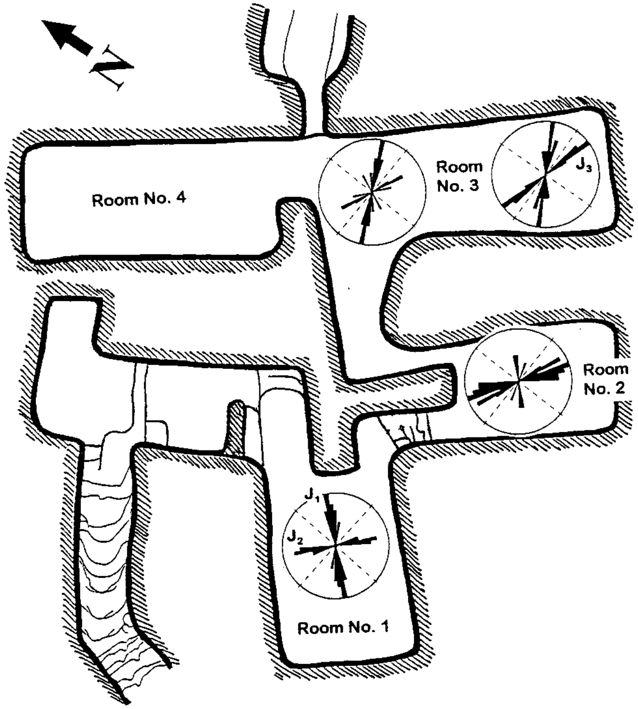
b

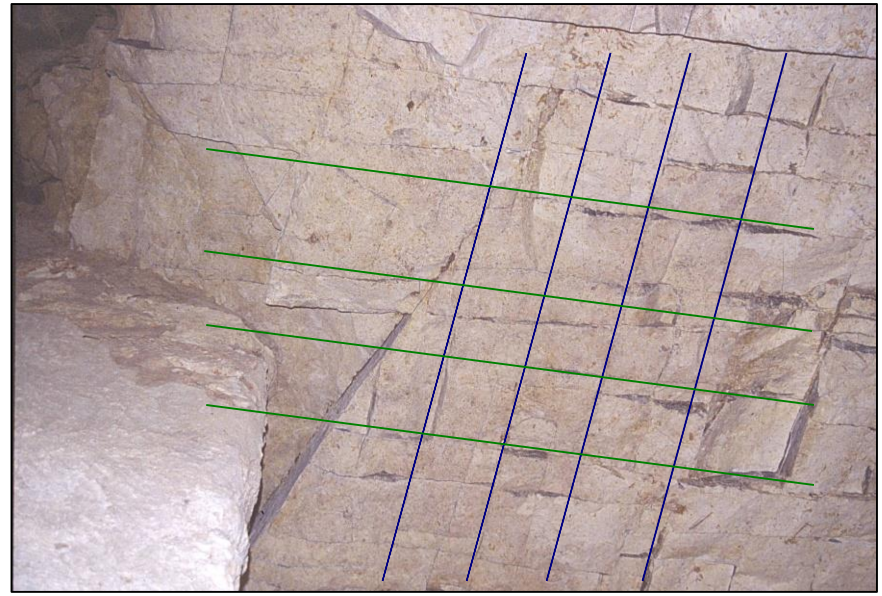
b

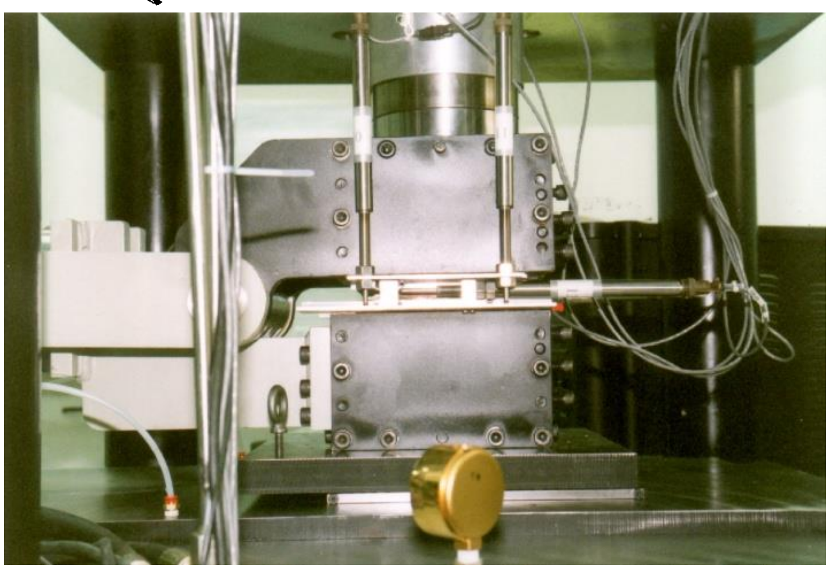


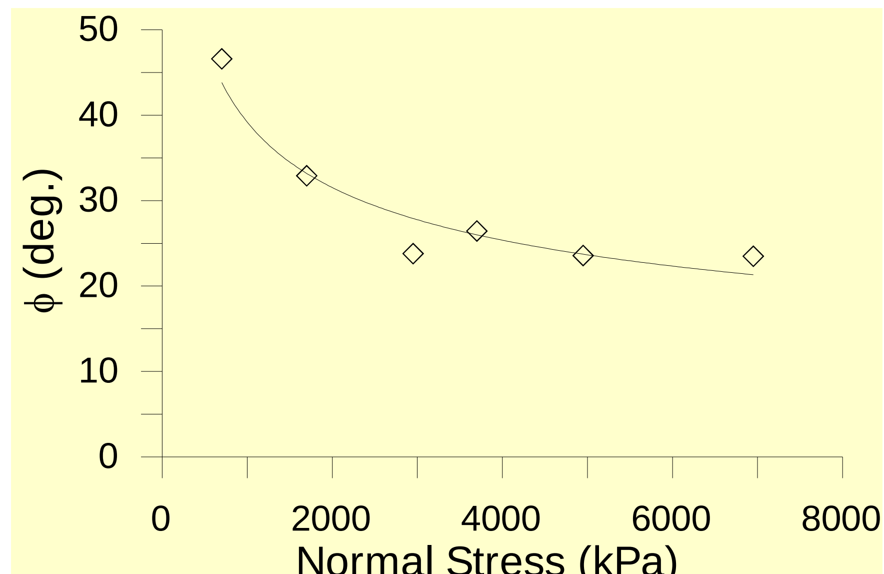
The collapse which occurred during time of construction was supported by the ancient engineers with a massive stone pillar.

Joint spacing, orientation, and friction angle:





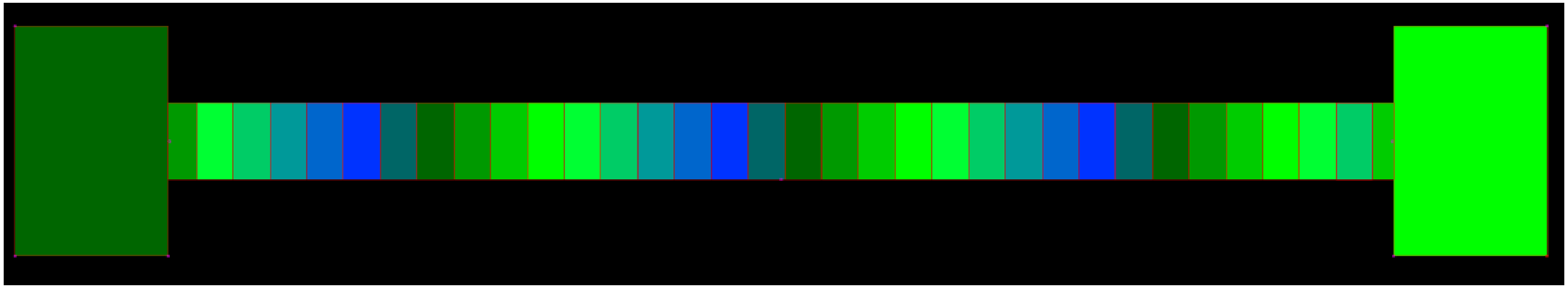




For the estimated level of normal stress the friction angle is assumed to be 35º

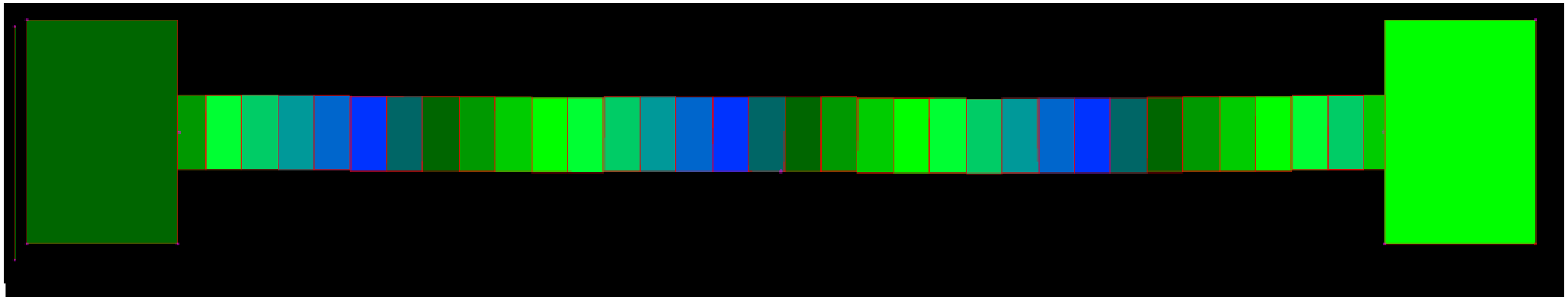
Kinematics of a Jointed Beam (Voussoir)

$S = 8\text{m}, t = 0.5\text{m}, S_j = 0.25\text{m}$



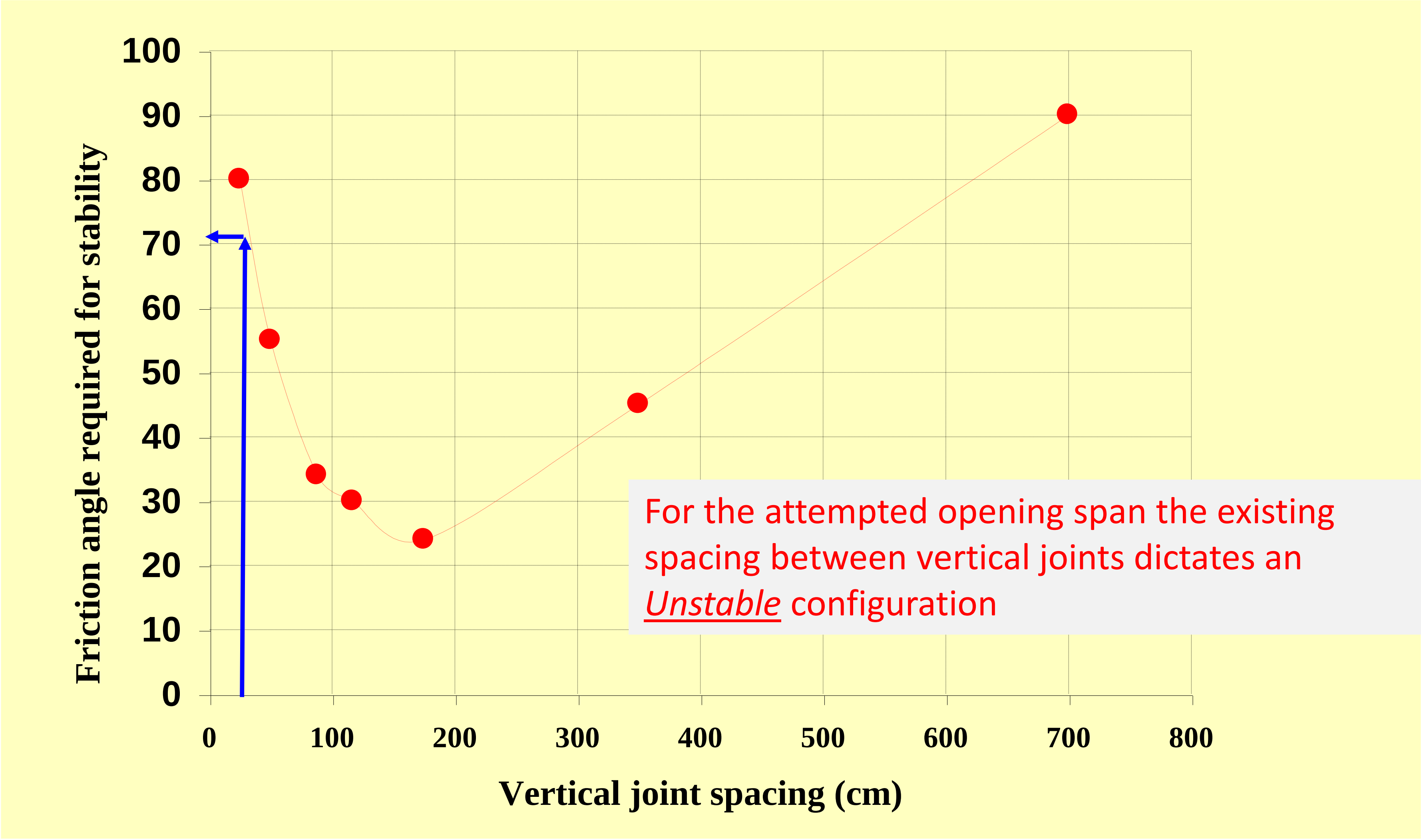
Initial Geometry

$\phi =$ [illegible]



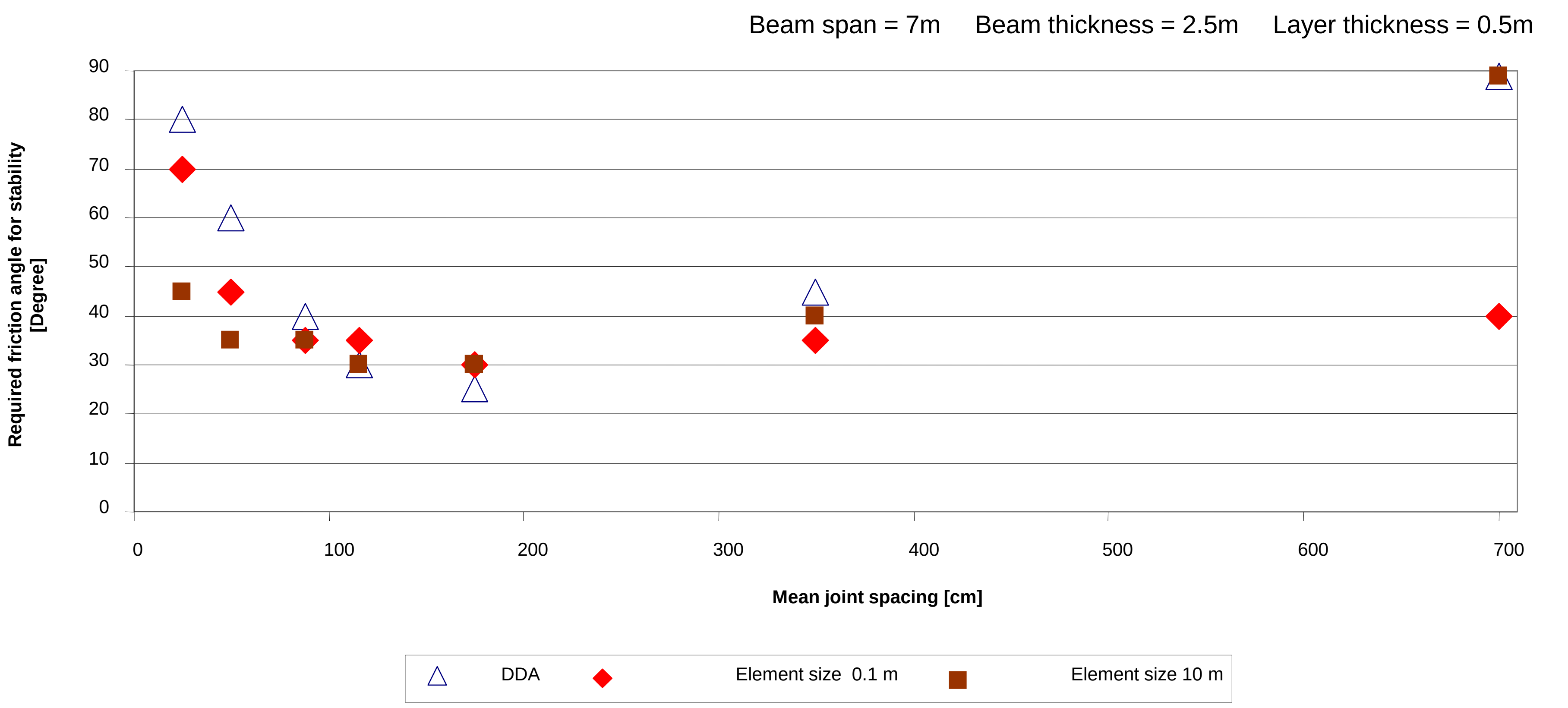
Deformed state

Forward DDA modeling results proves to be a function of vertical joint spacing and friction angle:



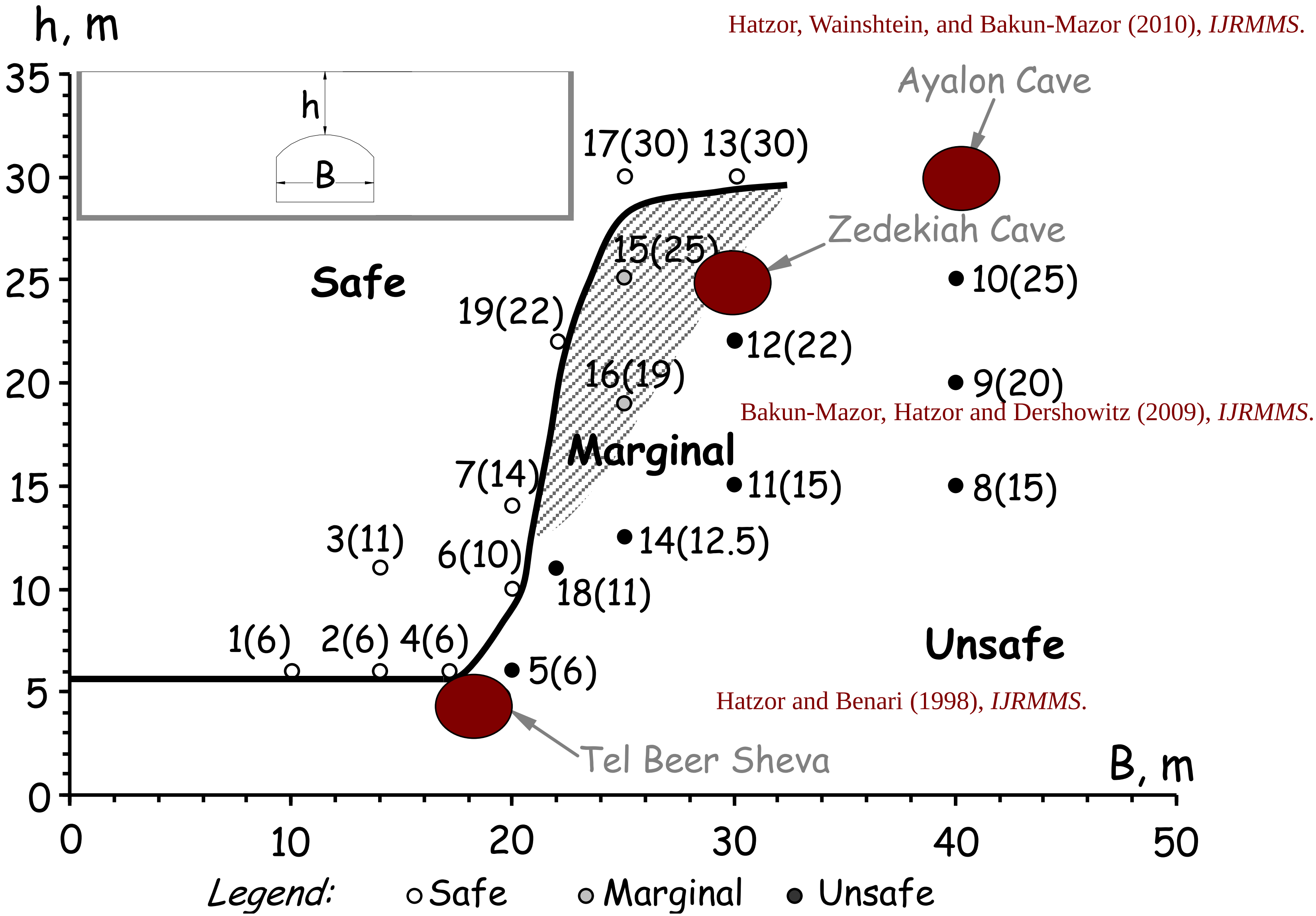
For the attempted opening span the existing spacing between vertical joints dictates an *Unstable* configuration

DDA vs. UDEC



Barla, Monacis, Perino, and Hatzor (2010), *Rock Mechanics & Rock Engineering.*

The numerically obtained relationship between *B* and *h* with the case studies shown:



Summary

- ***Sinkhole collapse*** **can pose a significant risk for people and surface civil engineering operations.**
- **We develop here, using the numerical DDA method, a function that marks the boundary between *Stable* and *Unstable* shallow cavern geometries, for blocky rock masses consisting of horizontal bedding planes and vertical joints.**
- **Our results are confirmed by three independent stability analyses of underground openings in blocky rock masses possessing different mechanical properties for intact rock elements as well as different joint friction and spacing.**