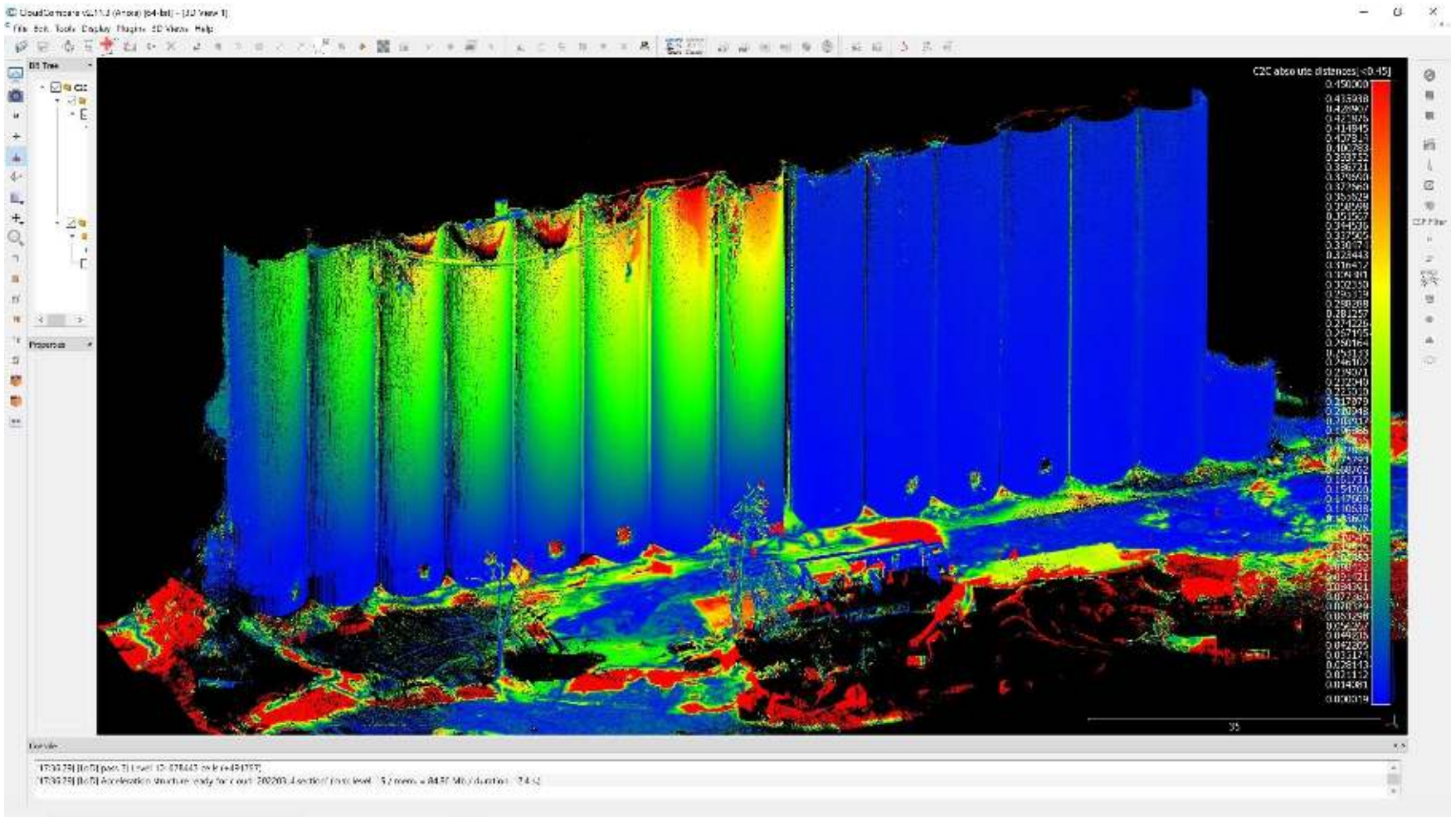
BEIRUT PORT SILOS

INTERIM REPORTING ON STRUCTURAL HEALTH MONITORING
GRAPHIC DOCUMENTS AND FAQ. VERSION 3.0. MARCH 7TH, 2022



BEIRUT PORT SILOS

INTERIM REPORT ON STRUCTURAL HEALTH MONITORING
VERSION 3.0. MARCH 7TH, 2022

TIMING OF OPERATIONS

August 25 th, 2020. Eng. Emmanuel Durand initiating support with 3D laser in Gemmayzeh / Mar Mikhael. (Amann / USJ)
September 17th, 2020. First 3D Imaging (laser scan) at the port silos at the invitation of the Lebanese Armed Forces. The Silo Expertise Group is created.
November 2020. Second 3D Imaging at the port silos, including 3D thermal to report on fermentation matters and grain temperature increase.
December 2020. Silo inspection and temperature measurements. Structural discussions (Silo Expertise Group). No laser scan.

BEIRUT PORT SILOS

INTERIM REPORT ON STRUCTURAL HEALTH MONITORING
VERSION 3.0. MARCH 7TH, 2022

TIMING OF OPERATIONS

March-April, 2021. Third 3D Imaging (laser scan) at the port silos. Complete report issued on May 08, 2021.
July-August 2021. Fourth 3D Imaging (laser scan) at the port silos. Installation of 4 X ultraprecise, autonomous Long Range Low Power ("LoRa") triaxial inclinometers, and their 4G LoRa router. Initiating live monitoring.
December 2021. Fifth 3D scan mission cancelled due to ankle injury sustained by Eng. Emmanuel Durand, and surgery needed in Geneva.
March 2022. Back on feet and fifth 3D scan mission at the port silos. Computing / comparing data and editing the present report.

BEIRUT PORT SILOS

FINDINGS

North Block situation

The North Block has been rotating vertically (= tilting) by an average of **0.85mm per day** (seen at the top of the silos) since the August 04th, 2020 blast.

The rotation of the North Block is in direction of the explosion crater, so West to East.

The rotation speed is not linear, depends on weather (wind, rain) and season (sun orientation, ambient temperature).
Highest tilt measured up to 2mm/day.
Lowest tilt measured 0.2 mm/day

BEIRUT PORT SILOS

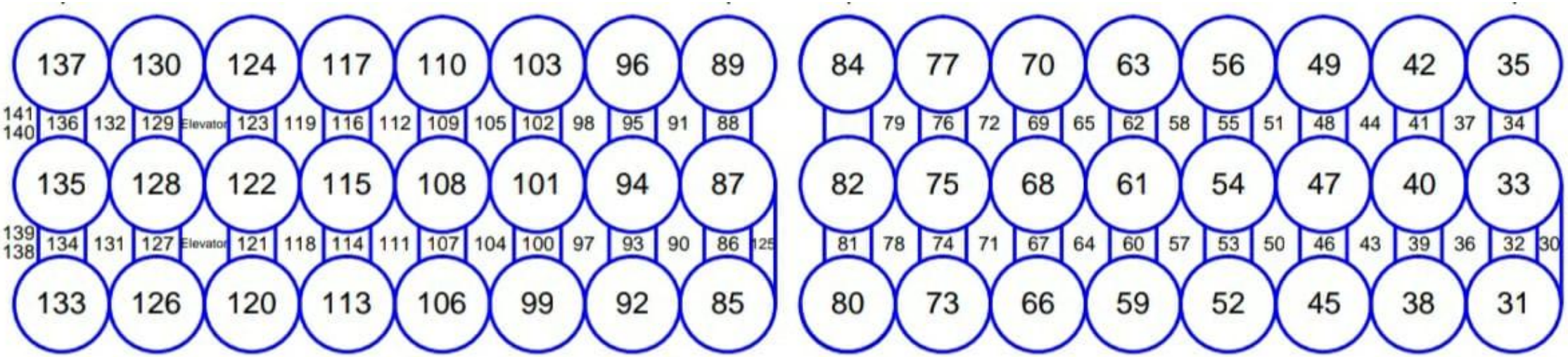
FINDINGS

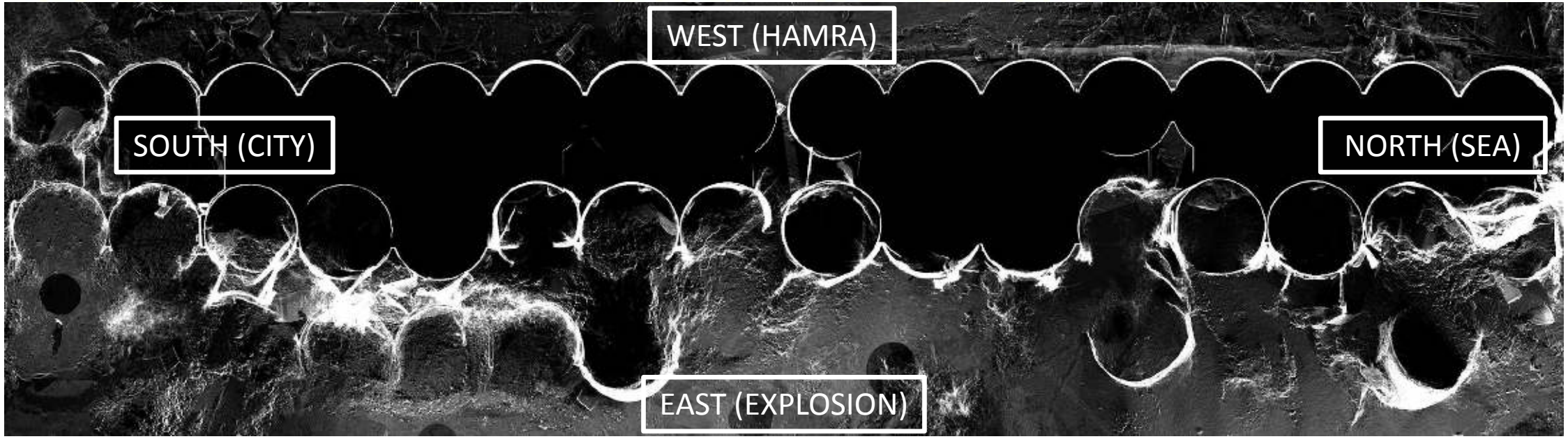
South Block situation

So far the South Block is **STABLE**.

The movements measured with laser scan are not significant.
Tilt measured by the inclinometers is consistent with normal seasonal trend of a high rise structure, change of temperature, change in sun orientation, etc…

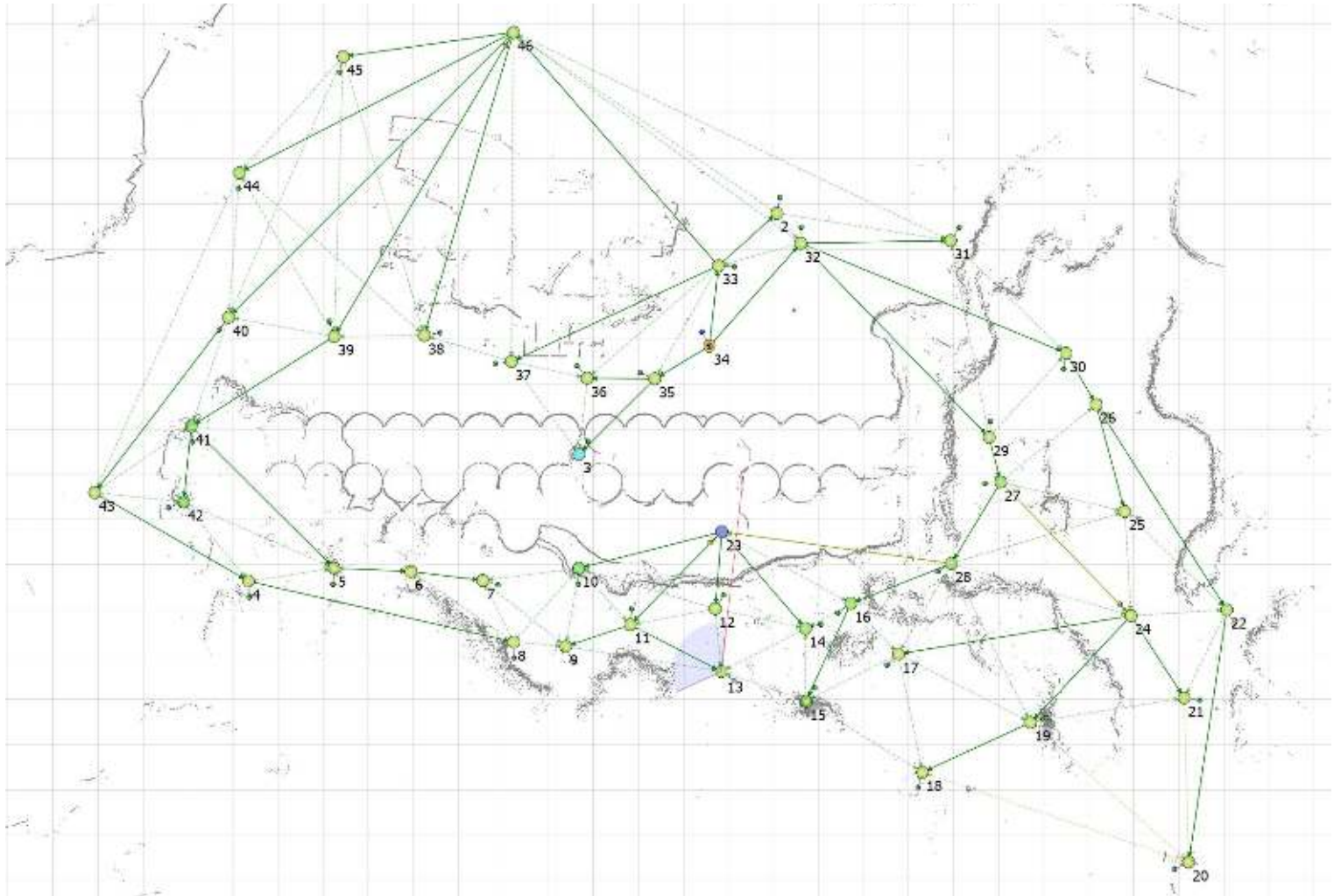
BEIRUT PORT SILOS NAME TAG





BEIRUT PORT SILOS

Laser Scan Stations and assembly. March 2022.



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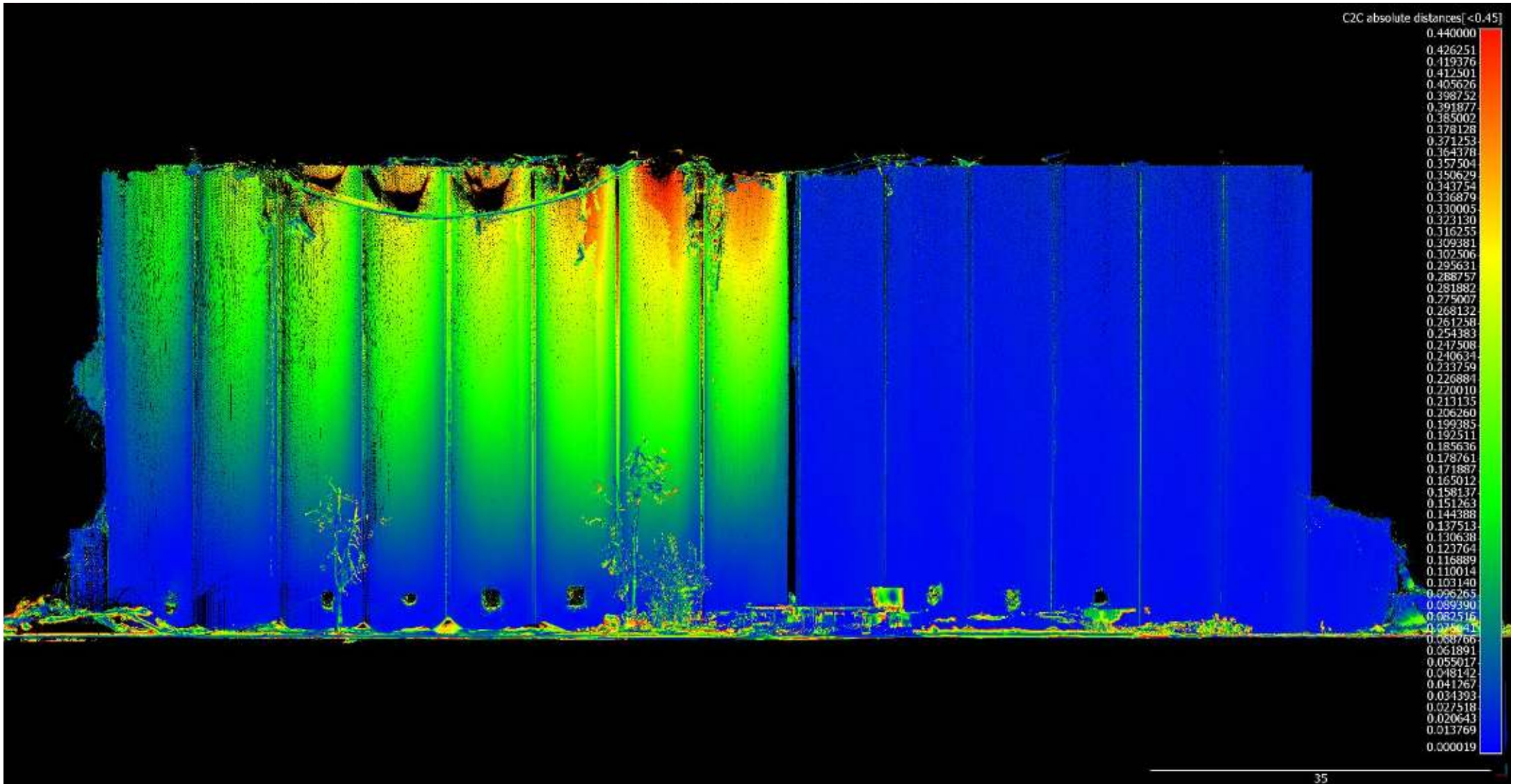
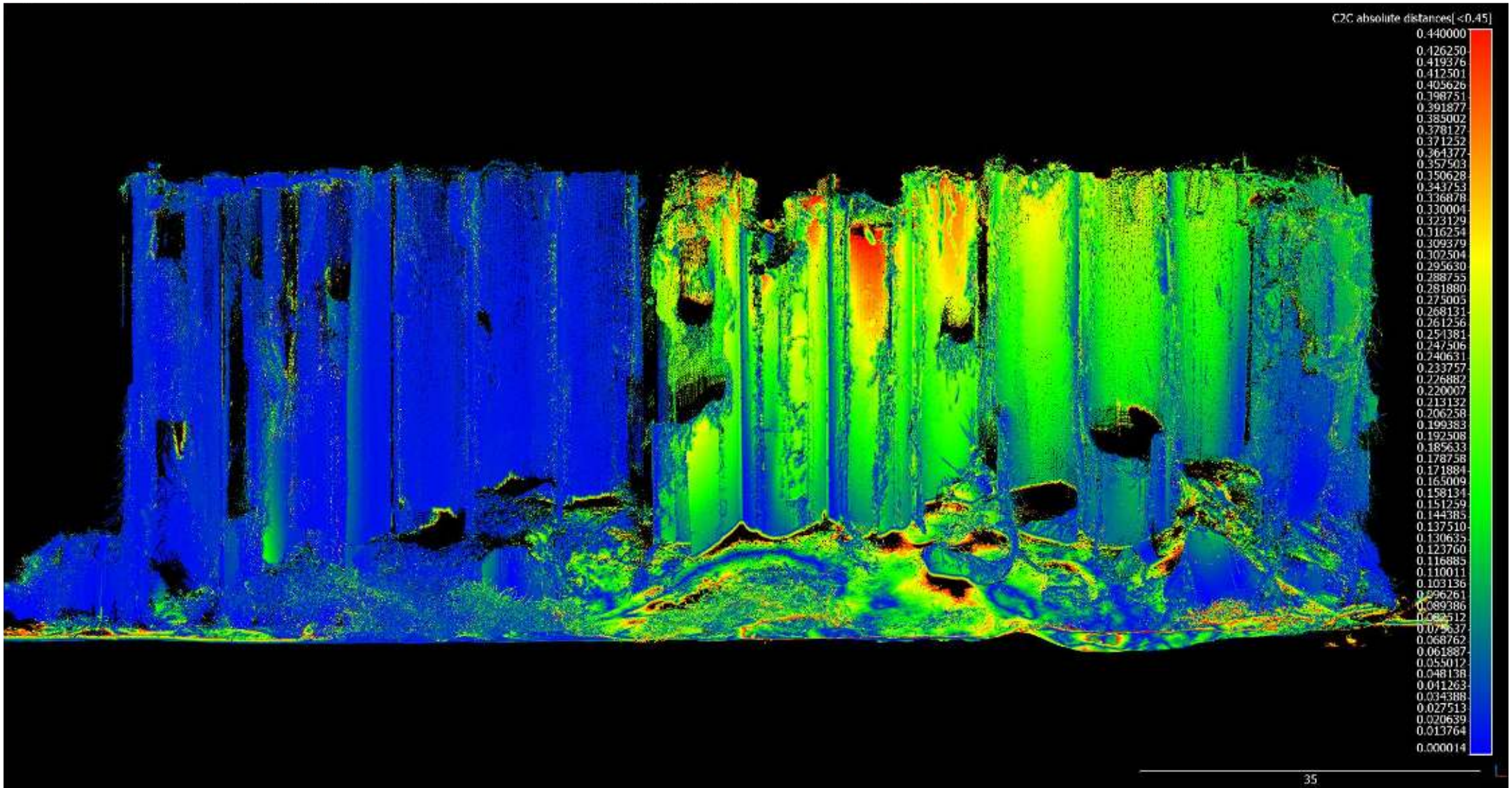
3D Comparison Sept.2020 / March 2022



Scale in meters

BEIRUT PORT SILOS

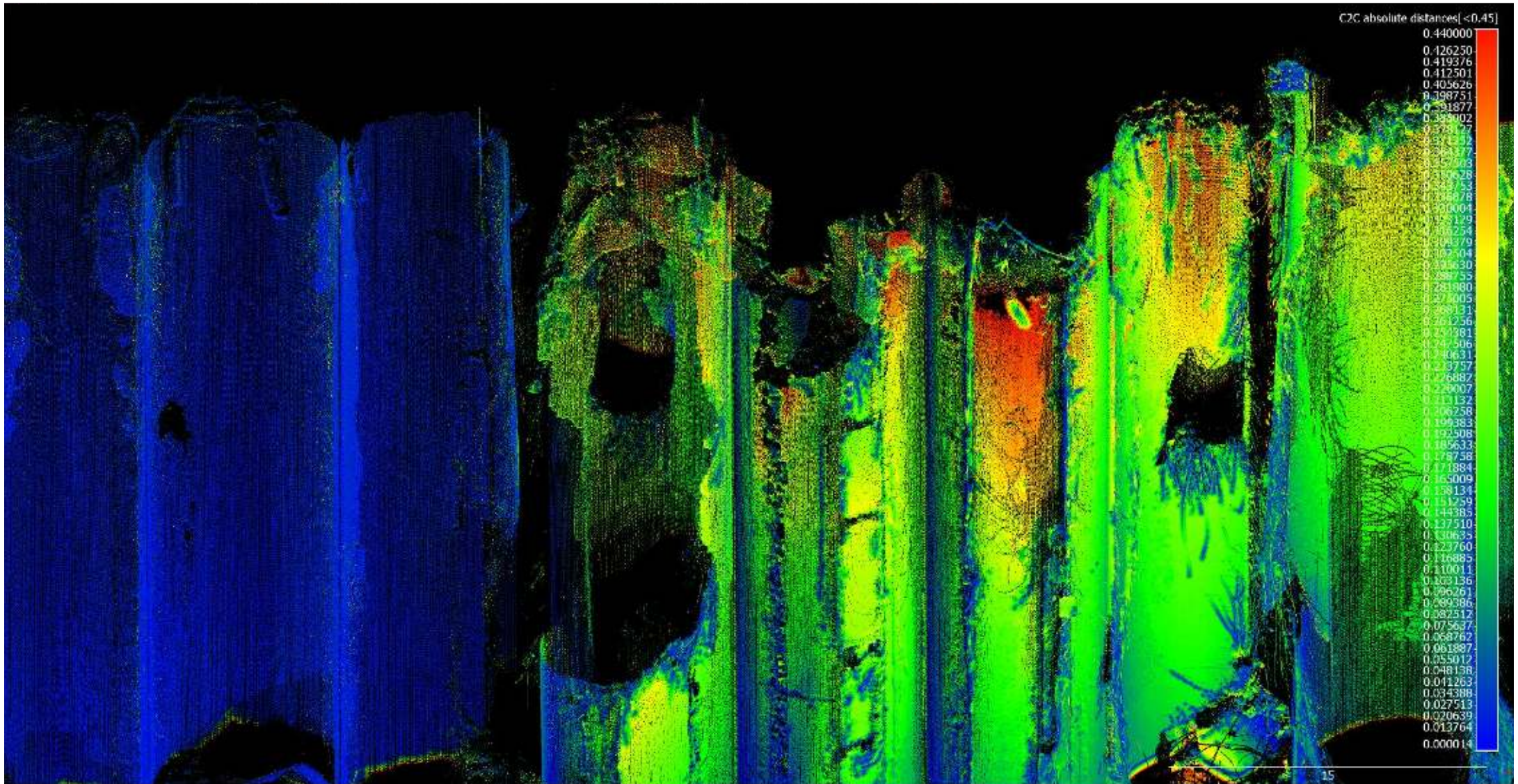
3D Comparison Sept.2020 / March 2022



Scale in meters

BEIRUT PORT SILOS

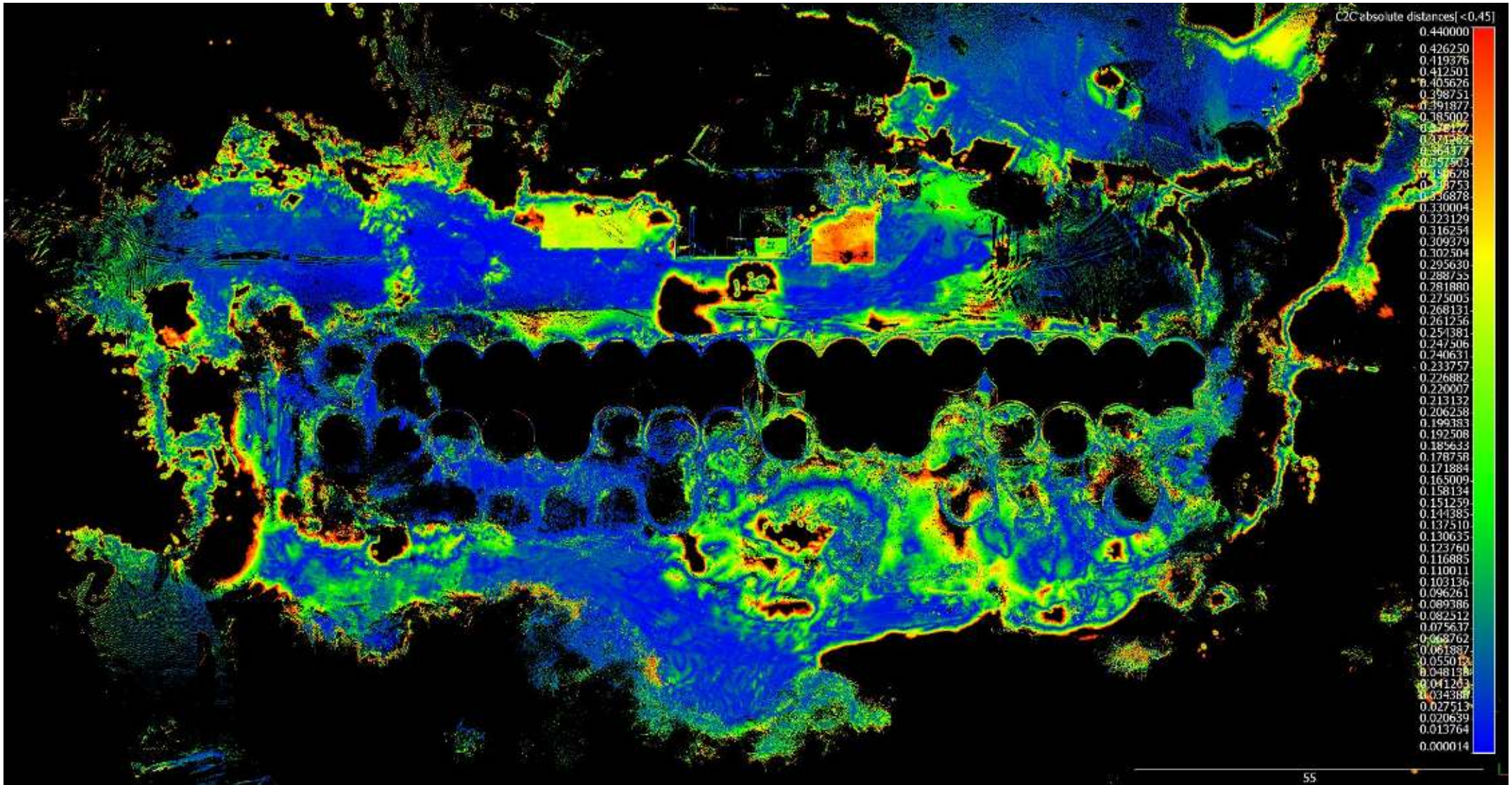
3D Comparison Sept.2020 / March 2022 (detail)



Scale in meters

BEIRUT PORT SILOS

3D Comparison Sept.2020 / March 2022

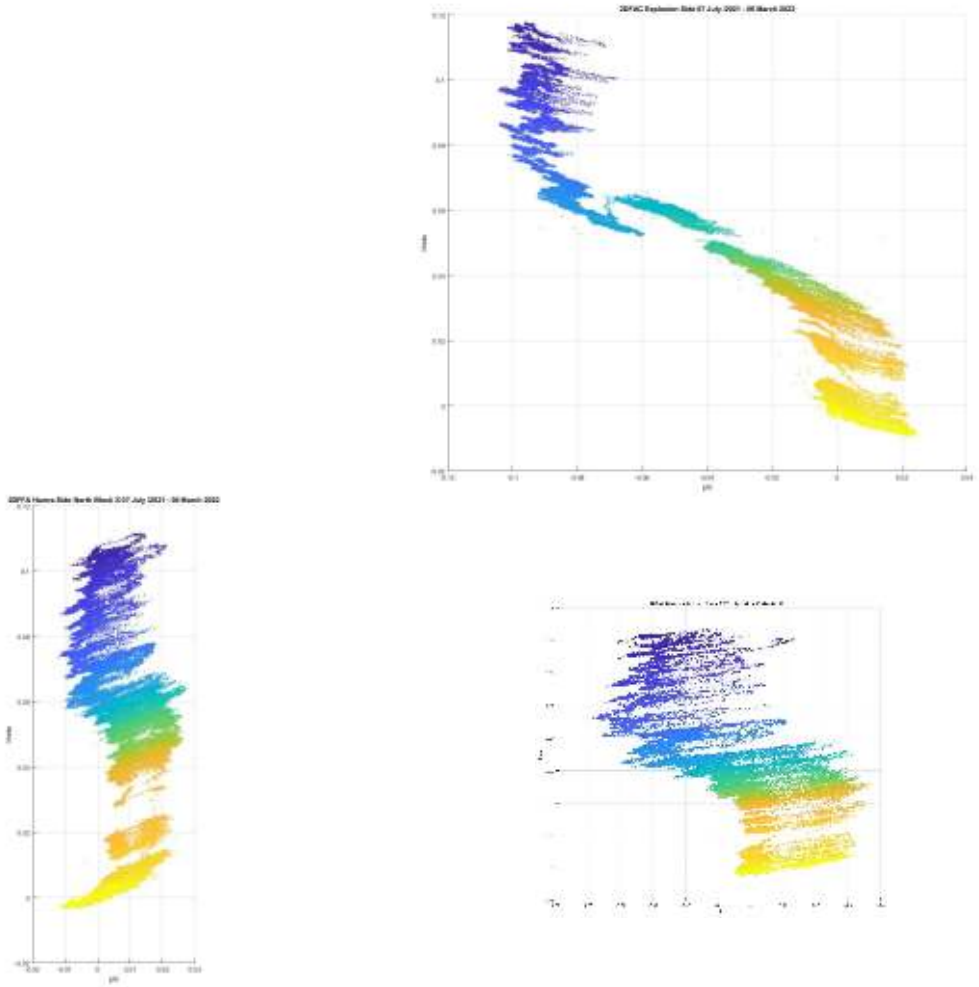


Scale in meters

SILO INCLINOMETER PLOT - PLAN VIEW

EAST (EXPLOSION SIDE)

NORTH



10 cm displacement equivalent at top of silo

SOUTH

The graph reflects the movements of the silo measured by each of the four inclinometers.
Color is related to date, yellow being July 2021, towards blue which is March 2022

WEST

BEIRUT PORT SILOS

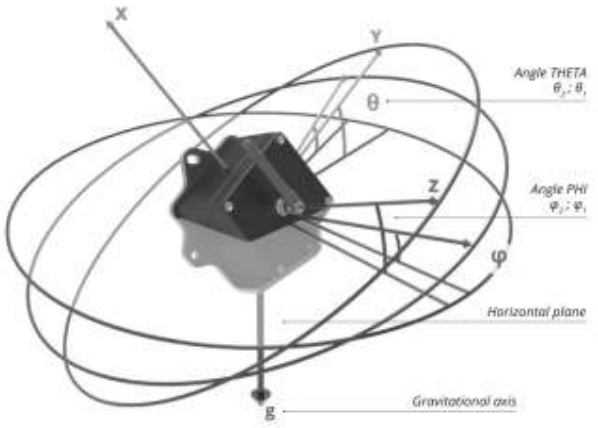
Principle of 3D Imaging / Laser Scanning

Laser scanning is a popular land surveying method that can accurately measure and collect data from objects, surfaces, buildings, and landscapes. Laser scanners collect information in the form of point cloud data, which consists of millions of 3D coordinates (XYZ coordinates).

In Beirut, every port silo scan campaign acquires one billion 3D points, or one point for every square centimeter of the silos. Every point is represented in space with millimeter precision.

Different 3D campaigns can be matched and compared, to identify which areas are moving and by how much.

BEIRUT PORT SILOS



Principle of inclinometers

An inclinometer is an instrument used for measuring angles of slope, elevation, or depression of an object with respect to gravity's direction. It is also known as a tilt indicator, tilt sensor, tilt meter,...

In Beirut, we installed four inclinometers in strategic locations:

- two inclinometers on North Block, Hamra side
- one inclinometer on North Block, explosion side
- one inclinometer on South Block, Hamra side

The inclinometers are sending information every two minutes

- “roll”
- “tilt”
- temperature of sensor (“contact temperature”)

BEIRUT PORT SILOS

FINDINGS

Why combine Laser Scan AND Inclinometers

The **inclinometers** provide live information about angular situation, with the precision close to 1/100 000 of angular degree, and every two minutes. The live measurements are limited to four specific individual points of measurement (3 on North Block, 1 on South Block).

The **laser scanner** provides 3D information over every surface of the structure that the laser beam can physically reach by just walking around the silos, plus one specific area right at the heart of the silos.
Laser scanning involves very significant computing power.

So the inclinometers and the laser scan complement each other.

Frequently asked questions

Will the silos tilt and fall into the sea?
No. The silos are heavily damaged/broken, they will collapse vertically on themselves once the current tilt makes the structural stress unbearable.

When the silos will collapse?
This is impossible to say as of now, because we are talking about an accidented structure. Technically, the structure lost its integrity due to the blast.
It can be a matter of a just a few months. At current speeds, the North Block would not stand more than a decade.

Will the sensors predict the collapse of the silos?
Structural health monitoring is not a predicting tool, but it does provide essential information about how the silos behave over time. Just like a heart rate monitoring device, but for a structure.
Thanks to that, alerts can be raised in case a significant change in trend is observed. Amann/SinA have raised three alerts to the silo group since September 2020.

Frequently asked questions

Can the current silos be restored/repaired?
No.
The silos are structurally beyond repair.
Any intent to “restore” “reinforce” etc… (whatever the term employed) would put lives at risk. At best, such intents would denature the silos as they are, alter their monumental expression. At worst, more people would get killed by falling debris, and possible local or total collapses while trying to do “something”.

Shall the silos be demolished?
That is a decision to be taken only by the different Lebanese stakeholders (families of victims, neighbours, government and others), by “Lebanon”.
The monitoring work by Amann / SinA provides facts, solid technical data we hope will help Lebanon to take the right decision, including and not limited to these linked with Memory considerations.

Frequently asked questions

If the decision is to <u>DEMOLISH</u>, how to proceed?
Different techniques exist but in the case of such a damaged structure the only **safe** methodology consists in using **ultra long reach hydraulic equipment**. Such equipments would have to be imported temporarily from abroad.

Using explosives or short reach hydraulic equipment would create more trauma and/or put more lives at risk. Such solutions cannot be considered.

If the decision is to <u>KEEP</u>, would that be safe / what would be the consequences?
If the Lebanese stakeholders (families of victims, neighbours, government and others) "Lebanon" decide to keep the structure, the silos will forever remain a risk in their immediate vicinity. Permanent monitoring will have to be maintained and even extended (more inclinometers, regular 3D campaigns, etc..). A very large safety area will have to be created and maintained all around the silos, with no access to the general public within it. The port logistics would also have to adapt to the footprint of a very large structure with memorial status, and take into consideration public access even it is from afar.

Frequently asked questions

Is it possible to keep the South Block and deconstruct the North Block?
Technically YES, that is possible but only provided ultra long reach equipment is employed for the careful deconstruction of the North Block.

Would it make sense to keep the South Block and deconstruct the North Block?
Again that is a decision to be taken by Lebanon, only.
It could be a good compromise among all stakeholders, by removing the biggest risk (the North Block tilt) and reducing the footprint of a dangerous area, while also giving more chance to Memory.

Can we demolish the silos and rebuild new ones at the same place?
Absolutely NOT.
The August 04th 2020 blast in Beirut is one of the biggest non-nuclear explosion. The explosion has created a crater about 100*100 m and up to six meters deep, so the underground component of the blast is huge.
There is currently as much damage inside the ground and below the silos, than what can be seen above ground on the superstructure. In particular, the concrete piles on which the silos are built have been

Frequently asked questions

shattered by the explosion, and for technical reasons it is not possible to “drive” new piles in between the shattered ones.

Still if decision is made to rebuild at the same location, what will happen?
First of all, rebuilding at the same location means new construction would not start immediately.
Second, before any construction happens new piles would have to be driven into the ground and we believe that would be more than extremely challenging, to say the least.
It is important to understand that the existing silos are built on a forest of 3500 concrete piles of 30cm*30cm section. That is one pile per square meter of ground.
The challenges of trying to drive new piles within a tight environment of the existing broken ones would inevitably translate into claims and delays, not even talking about frustration shall the task be later confirmed as technically unsurmountable (“silos demolished for nothing”).

Frequently asked questions

Any recommendation at this point?
Focus shall be put on priorities:
- clear all other platforms at the port, to make space for new warehouses.

- fund, design and build new silos an loading/unloading systems. New silos would have to be built anywhere but at the current location.
Building at a new location also presents the advantage that construction would start as soon as funding is made available, and with no special technical challenge since “fresh ground” would be used and no rubble/steel bars inside.

- take all the necessary time to discuss the future of the existing silos with all the stakeholders. As long as the existing safety area is maintained, demolition is not a priority compared with other challenges within the port of Beirut.

Frequently asked questions

Why are the silos tilting?
The North Block was built first in the 70's. It is more into the sea and piles are longer than from the South Block. Piles are more slender, and they were not designed to resist a lateral stress such as the one created by the underground component from the blast.
The piles are now broken and the closer to the explosion epicenter the more broken. That is why the North Block currently "sinks" in direction of the explosion crater.

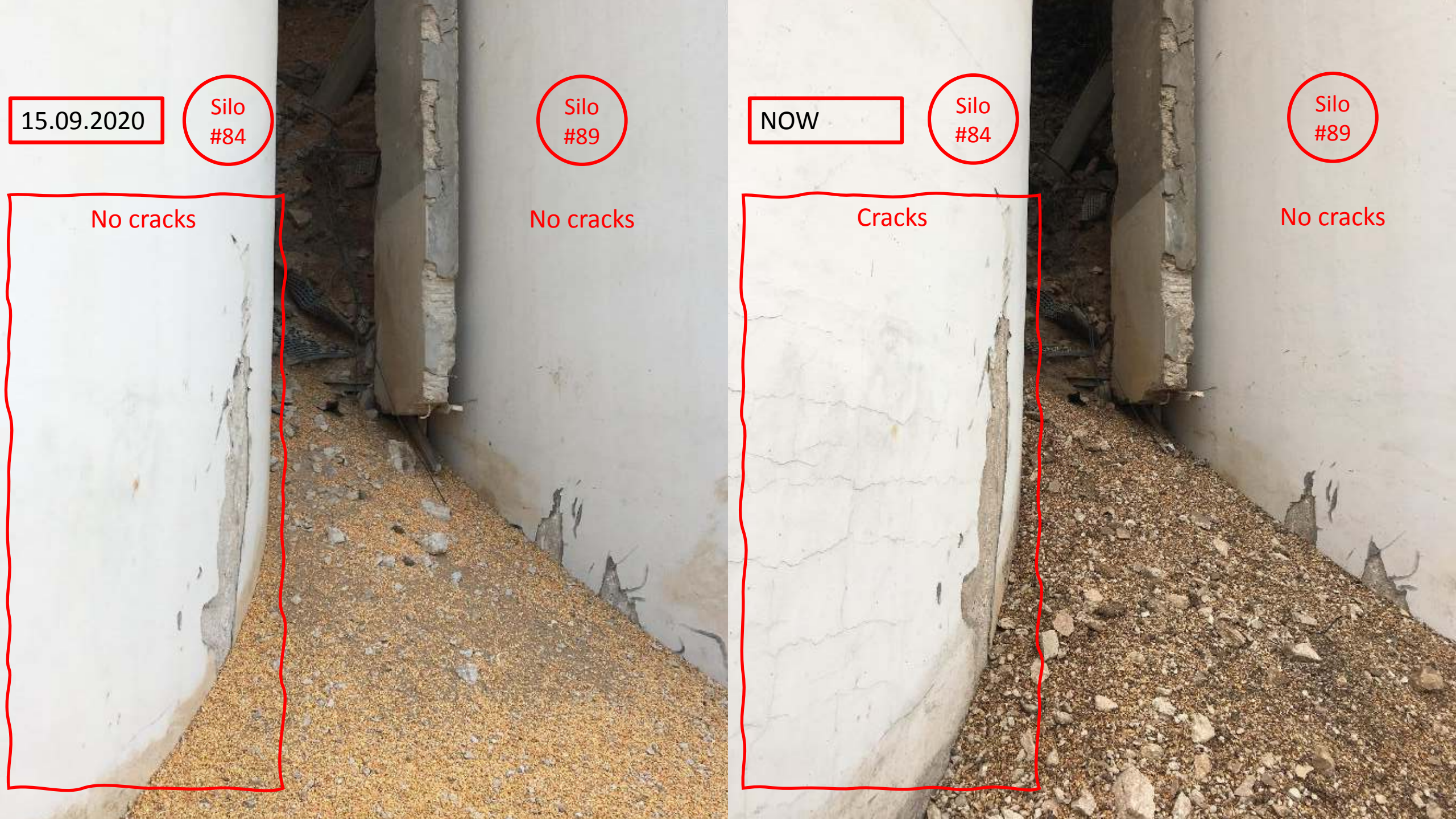
The South Block piles are shorter (=less slender), they were built better since the South Block was built as a phase 2.

What is the current trend of the tilt?
The tilt is subject to temperature and weather conditions like wind and rain, overall structural conditions especially below ground among other factors.
At the moment and since January 2022 an **acceleration** of the tilt is noted, certainly linked with bad weather and sharp changes in temperatures.

Frequently asked questions

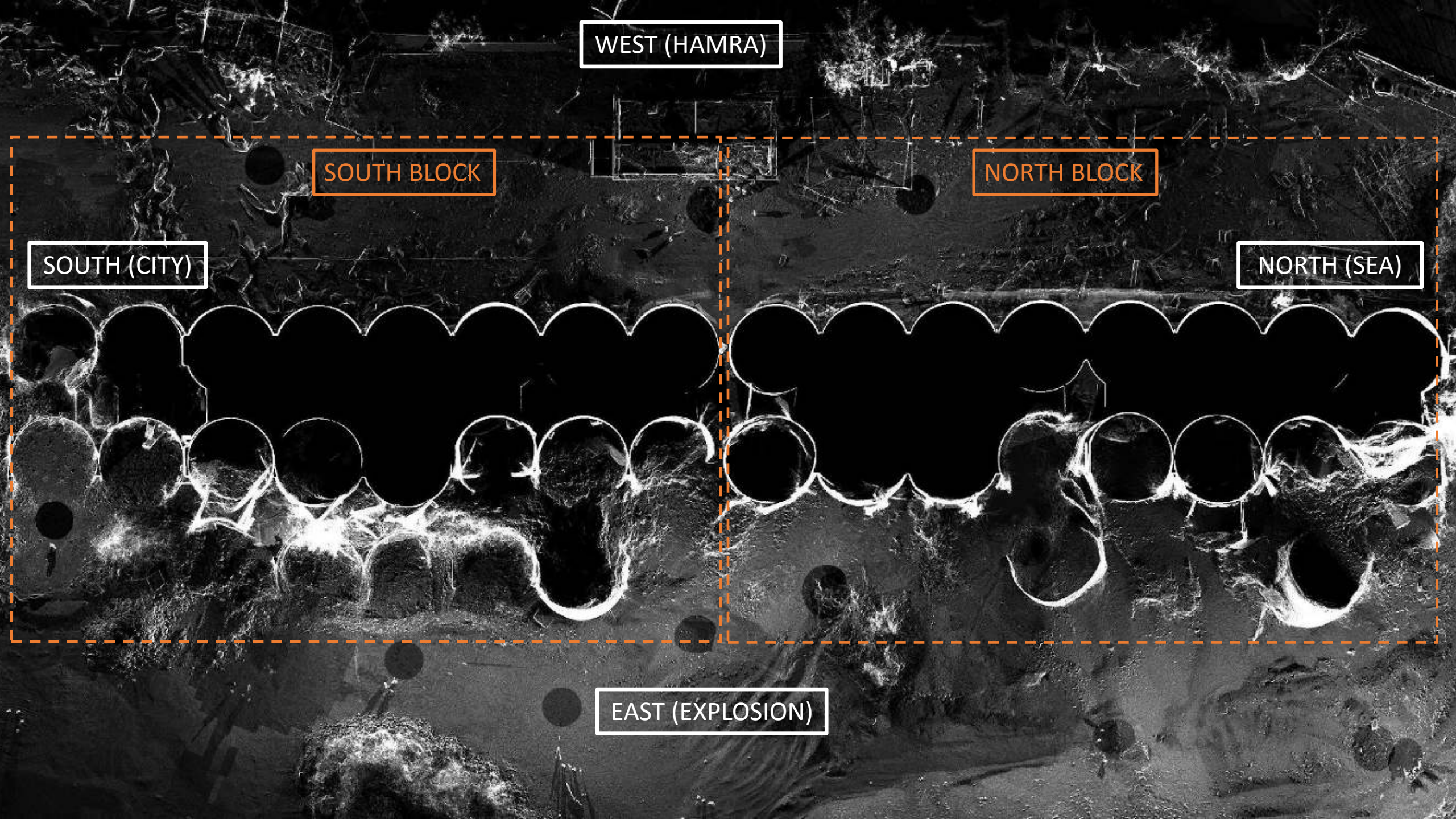
Who is funding/commissioning Amann / SinA?
Our work is purely that of volunteers. We started giving support in town (Gemmayzeh, Mar Mikhael) in August 2020, then naturally evolved towards technical support on the Port Silos at the request of the LAF and since silo structural assessment of Amann Engineering GmbH ("Amann", based in Geneva).
Amann has only received symbolic funding from USJ, AUB and the Swiss Federal Institute of Technology (ETH Zürich). SinA "Scan in Action, Geneva" is our NGO arm based.
SinA has received in kind support from Zöller+Frohlich GmbH in Germany with the loan of 3D laser scanner, software and high resolution panoramic thermal cameras. SinA also has constant support from companies Move Solutions (Milano, Italy) and Smartec (Lugano, Switzerland).

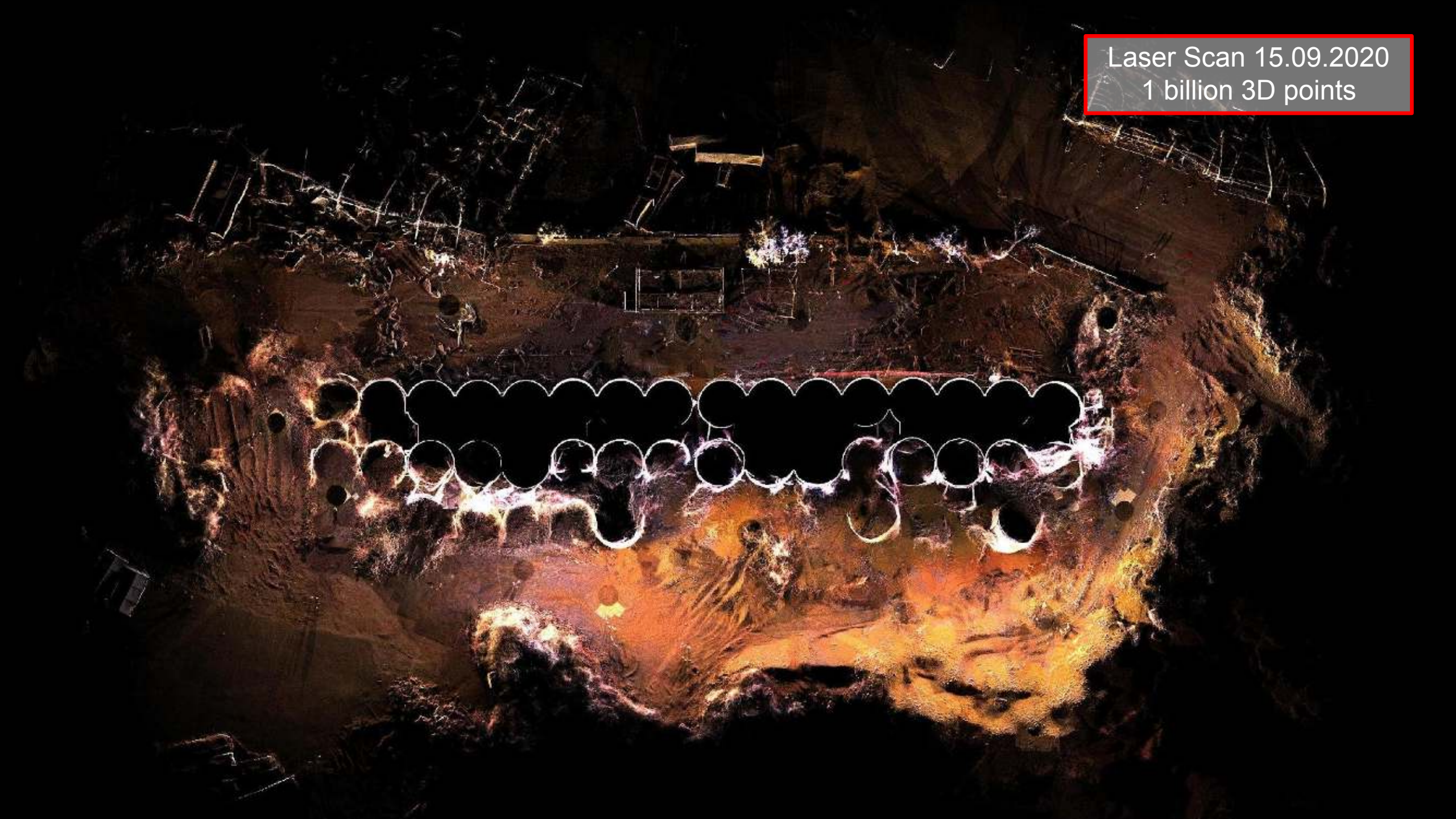
How can we use 3D imaging (laser scan) of the silos in the future?
Laser scanning technique is a solution of choice everywhere in the world when heritage considerations are important. It is used currently in the reconstruction of Notre Dame de Paris (the roof and timber frame had been surveyed a few years before the fire).
In Beirut our successive 3D scans form detailed picture in three dimensions and at different times. There is no real limit to how the data can be used later (museum, cinema, historical studies etc…).


15.09.2020
Silo #84
Silo #89
No cracks
No cracks
NOW
Silo #84
Silo #89
Cracks
No cracks

Typical crack measurement on Silo 84.
0.45 mm is very significant for this kind of damage.
Cracks are observed on the outer silo plastering AND the structural concrete (means, the damage is not superficial but deep).


Laser Scan 15.11.2020
1 billion 3D points

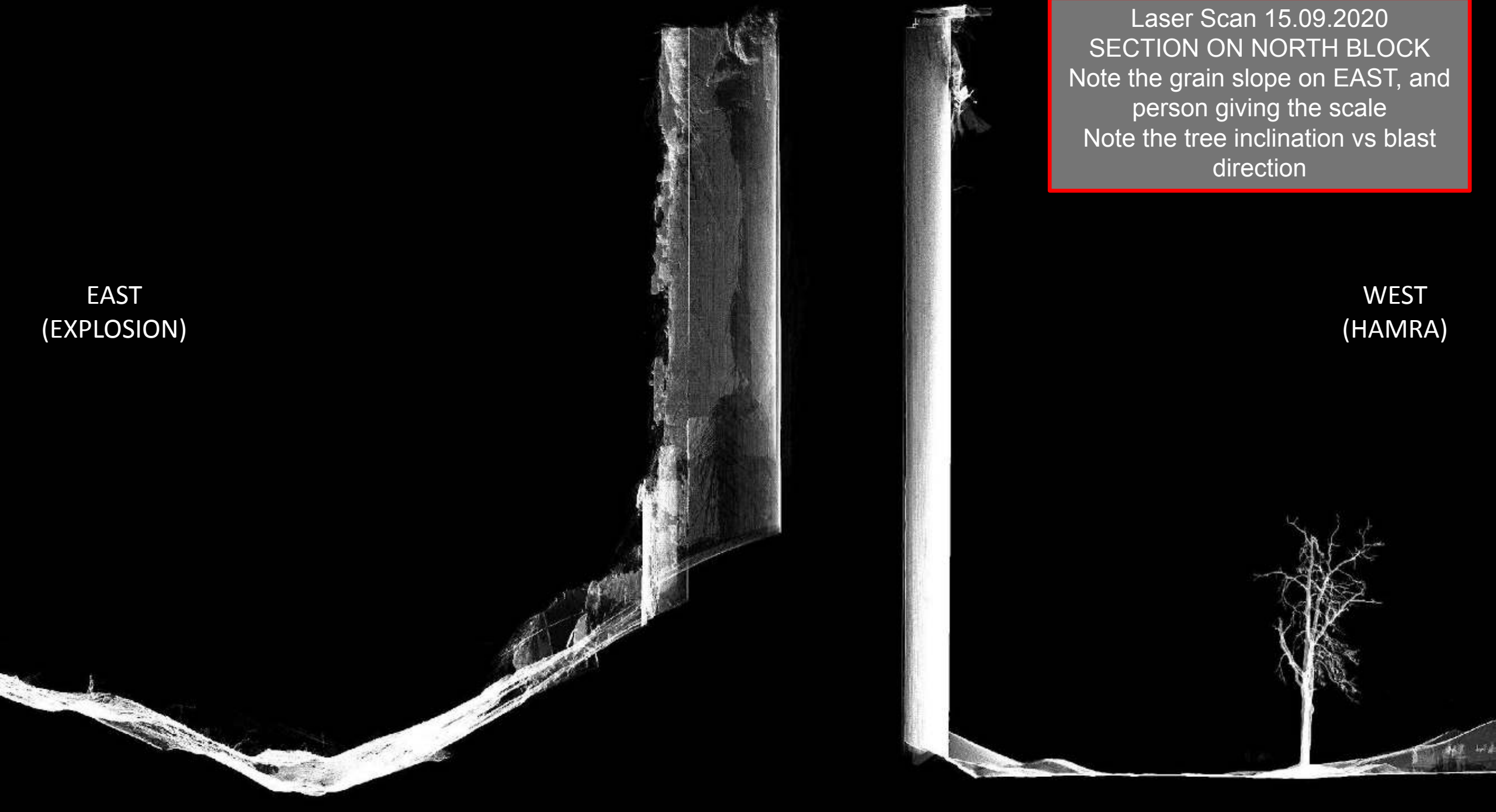

WEST (HAMRA)
SOUTH BLOCK
NORTH BLOCK
SOUTH (CITY)
NORTH (SEA)
EAST (EXPLOSION)

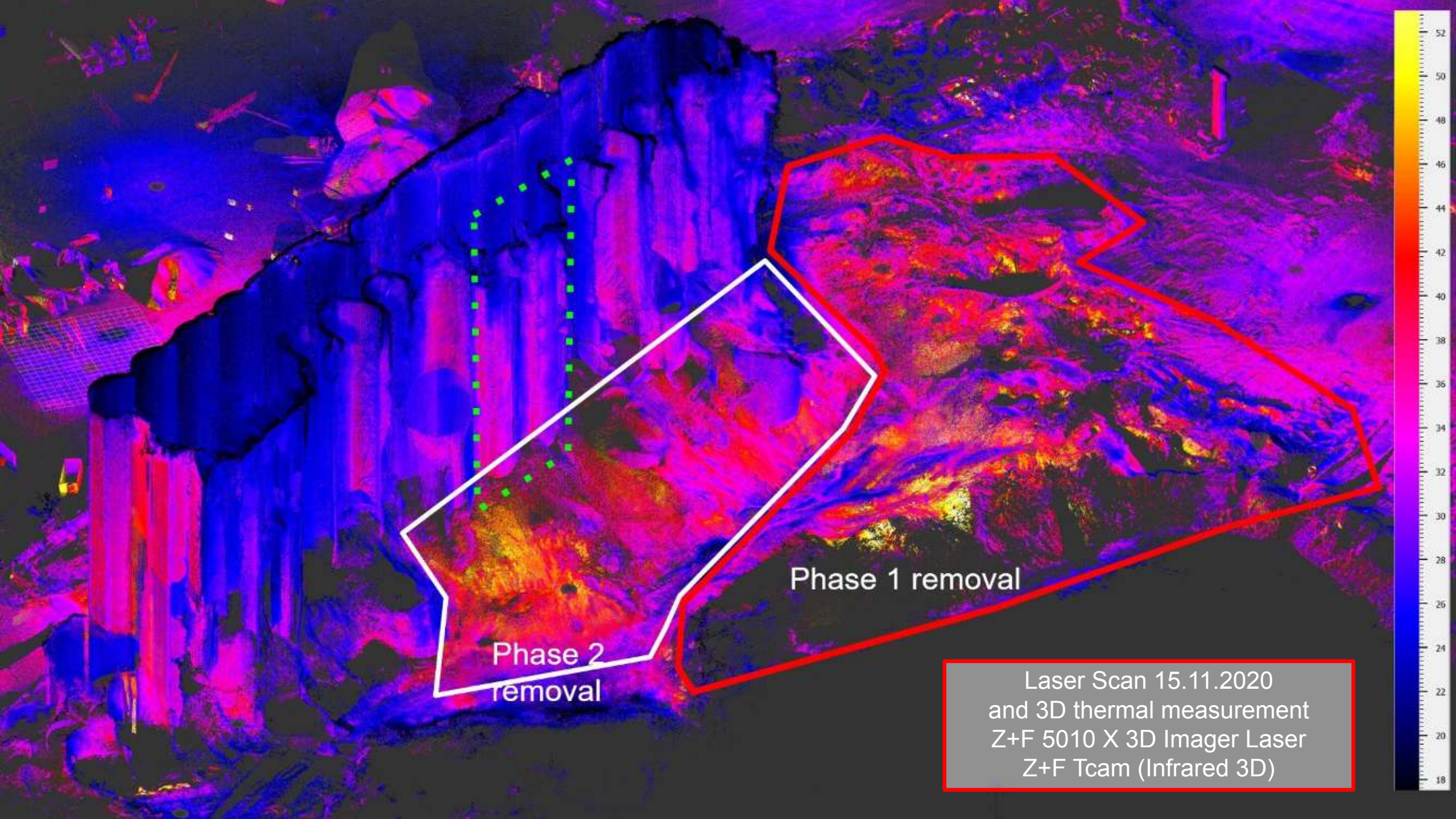

Laser Scan 15.09.2020
1 billion 3D points

Laser Scan 15.09.2020
SECTION ON NORTH BLOCK
Note the grain slope on EAST, and person giving the scale
Note the tree inclination vs blast direction

EAST
(EXPLOSION)

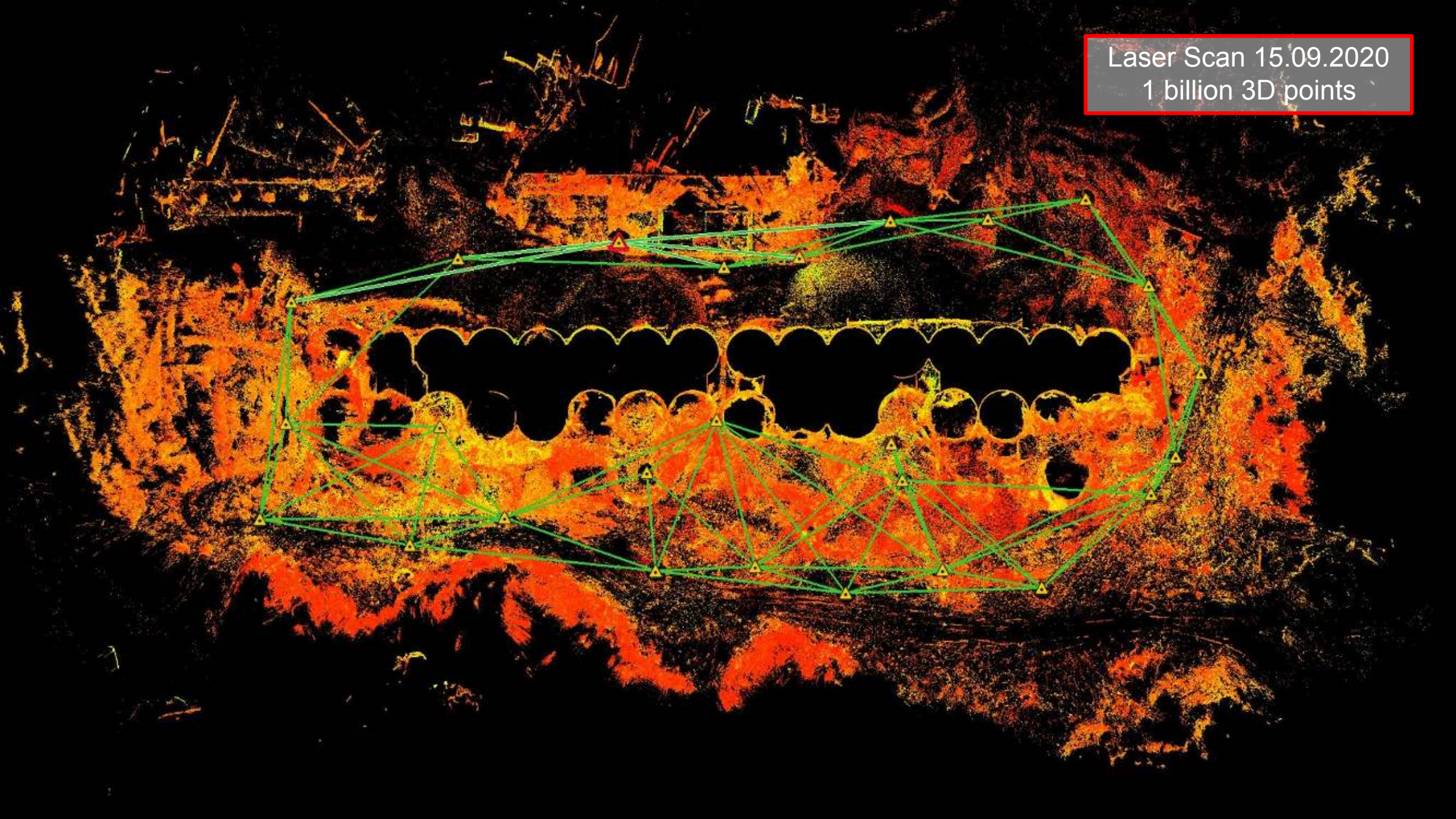
WEST
(HAMRA)





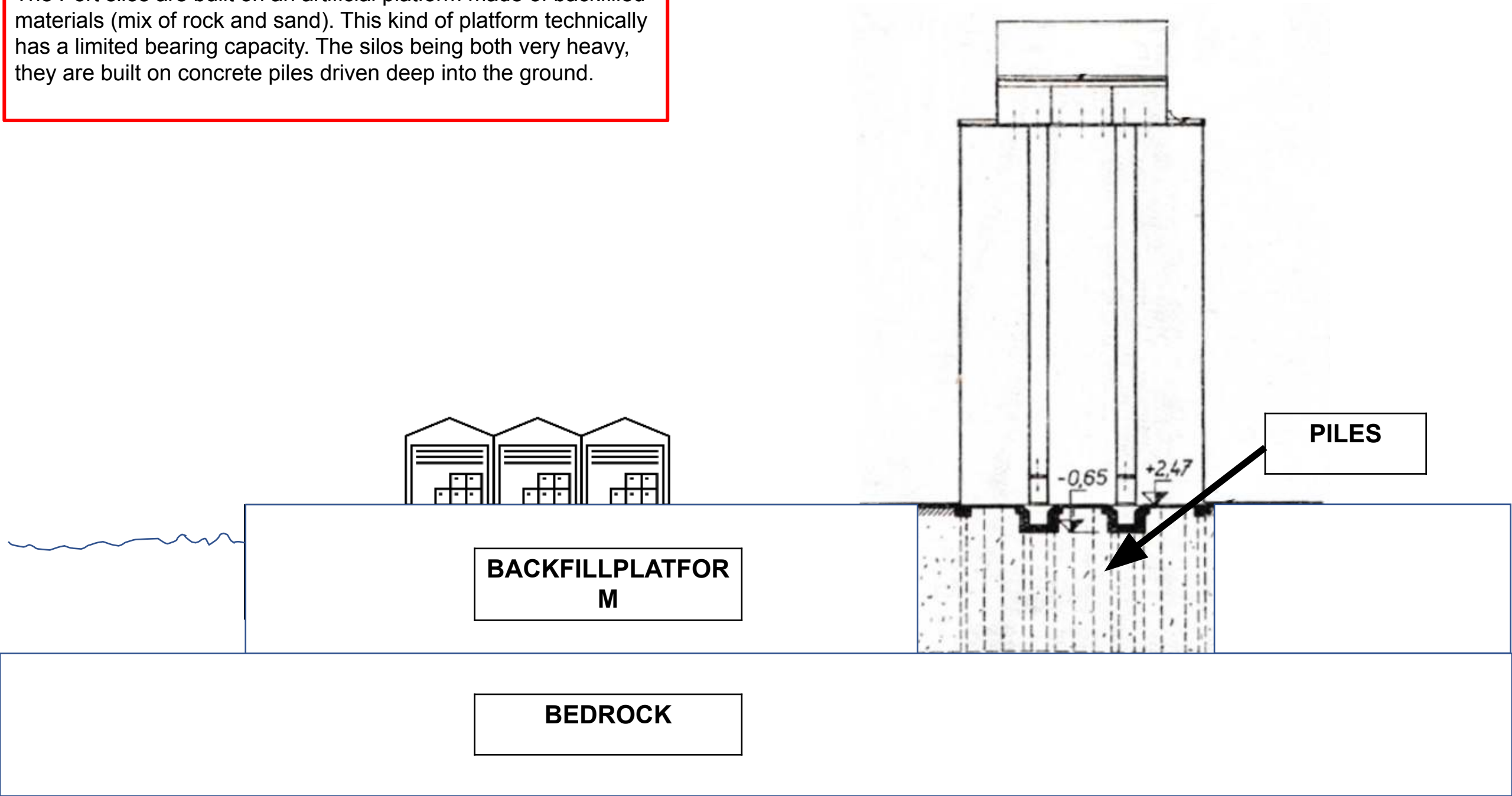
Laser Scan 15.11.2020
and 3D thermal measurement
Z+F 5010 X 3D Imager Laser
Z+F Tcam (Infrared 3D)


Laser Scan 15.11.2020
Z+F 5010 X 3D Imager Laser


Laser Scan 15.09.2020
1 billion 3D points

BEFORE THE BLAST / THE PORT PENINSULA

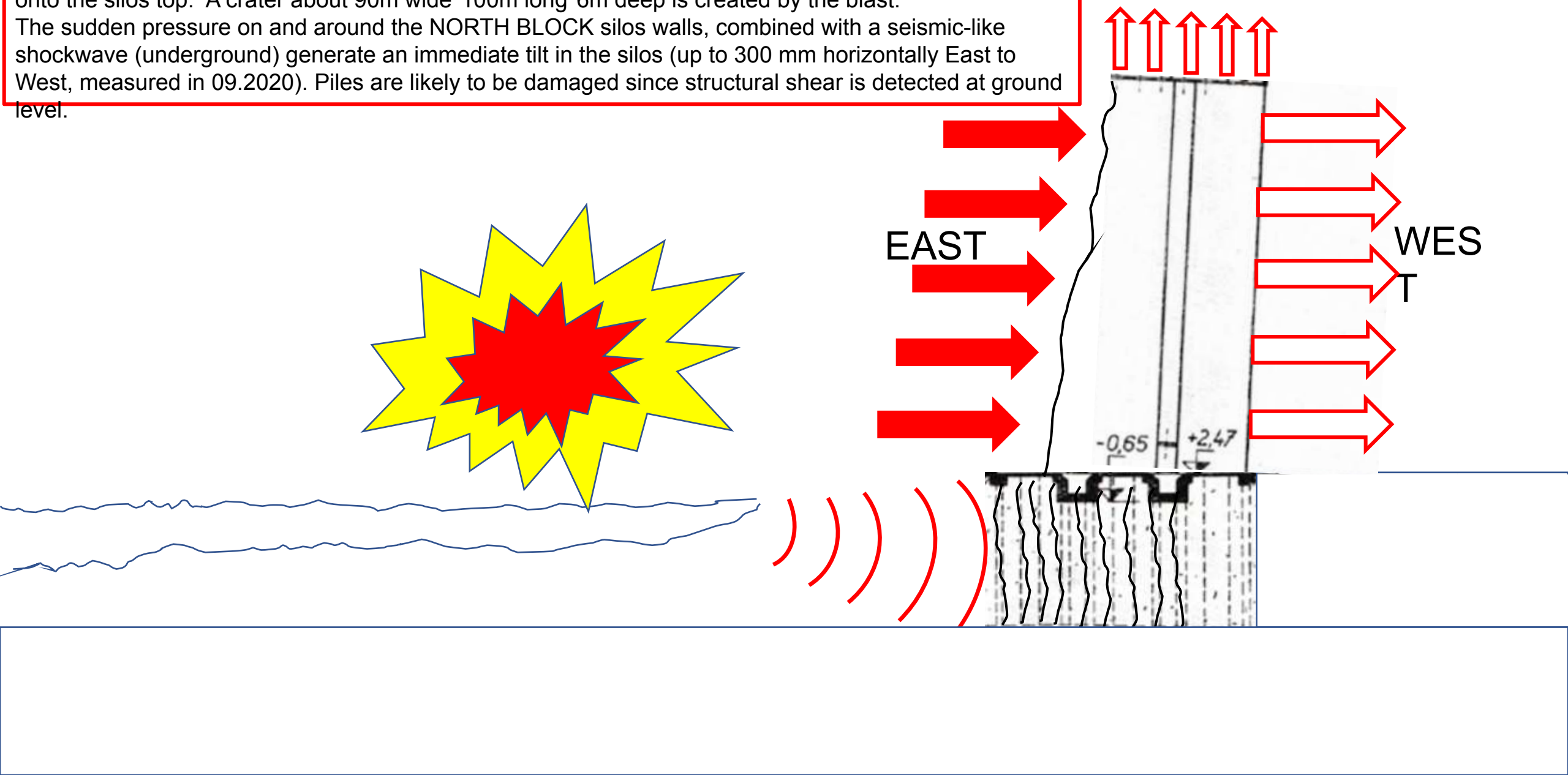
The Port silos are built on an artificial platform made of backfilled materials (mix of rock and sand). This kind of platform technically has a limited bearing capacity. The silos being both very heavy, they are built on concrete piles driven deep into the ground.



BLAST AUGUST 04 AND FIRST LASER MEASUREMENT ON SEPTEMBER 17, CONFIRMED WITH SECOND LASER MEASUREMENT ON NOVEMBER 23,

Port and town are hit. Due to difference of pressure (Delta P) the silo roof takes off, sits again crushed onto the silos top. A crater about 90m wide*100m long*6m deep is created by the blast.

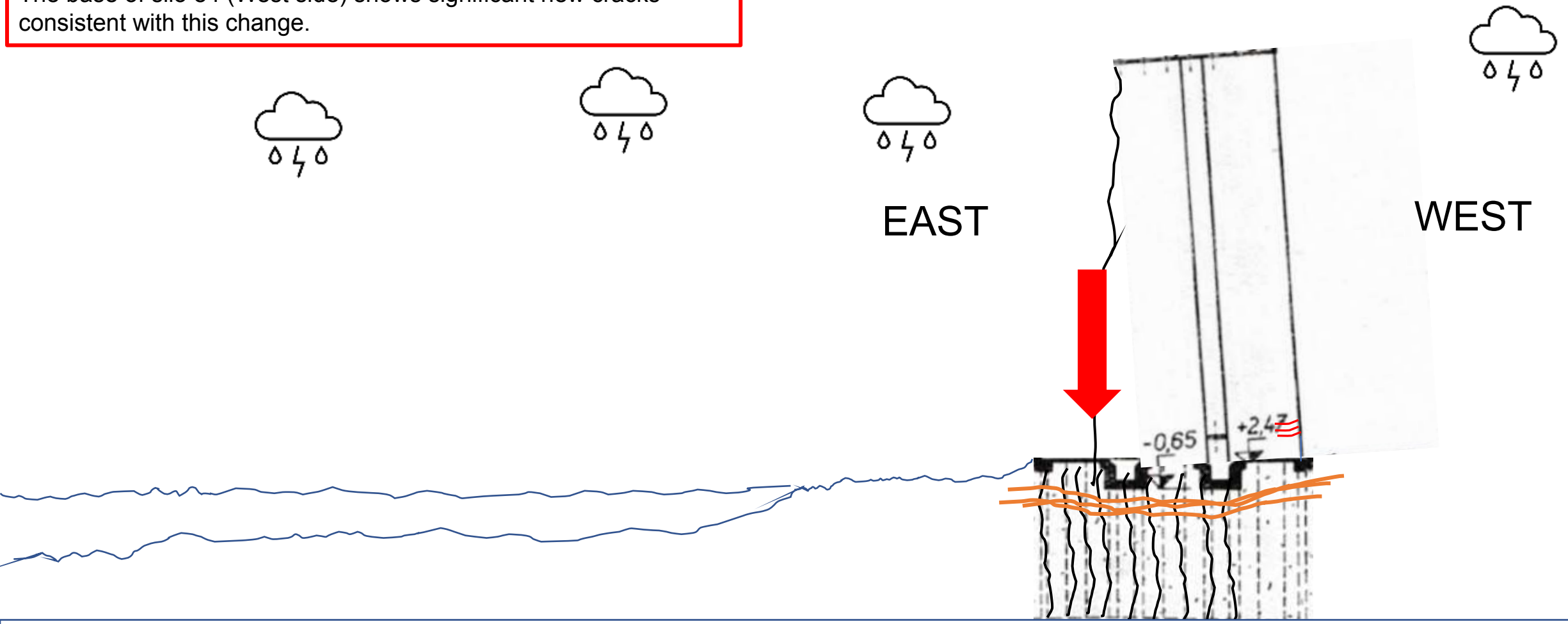
The sudden pressure on and around the NORTH BLOCK silos walls, combined with a seismic-like shockwave (underground) generate an immediate tilt in the silos (up to 300 mm horizontally East to West, measured in 09.2020). Piles are likely to be damaged since structural shear is detected at ground level.



THIRD LASER MEASUREMENT, MARCH 27

Silos inclination changes by up 250 to 300 mm at the top od NORTH BLOCK silos, likely due to settlement of the ground at bottom.

The base of silo 84 (West side) shows significant new cracks consistent with this change.



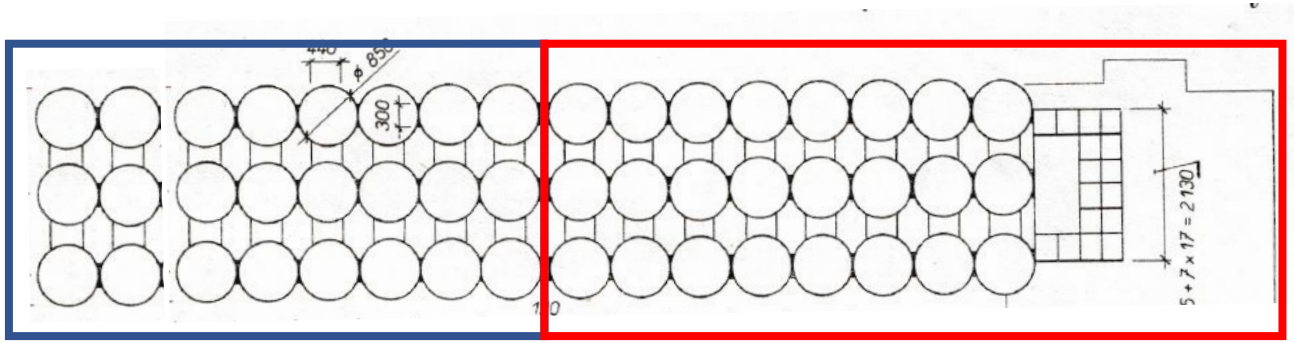
SOME HISTORY ABOUT THE SILO FOUNDATION PILES SLENDERNESS AT THE TIME OF CONSTRUCTION

Eng. KAREL KERHART, SPŠP Pardubice
Translated to English by Arch. GIOIA SAWAYA

Construction of a Grain Silo in Beirut

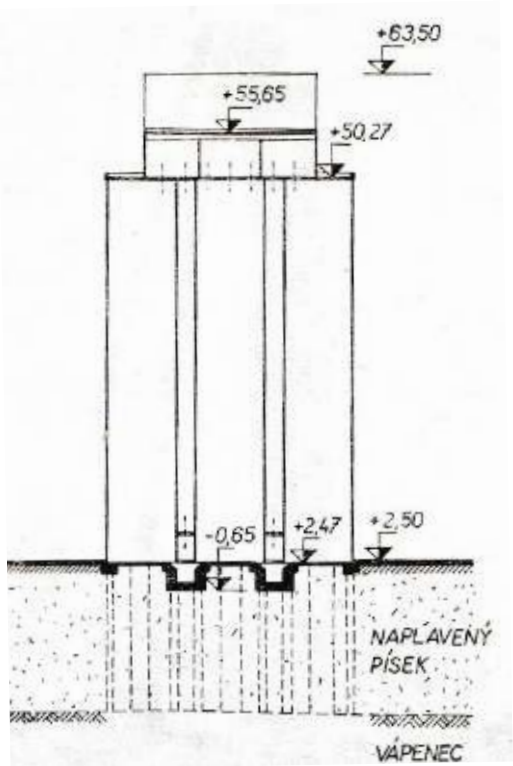
Průmstav, n. P., Pardubice built a grain silos in Beirut on 16 m-high reinforced piles in an alluvial layer of sand. During the construction, it was necessary to overcome numerous difficulties, both in the pile driving and in the construction itself. The article informs about the experience in local climatic conditions, and is of great importance for our companies that are penetrating abroad.

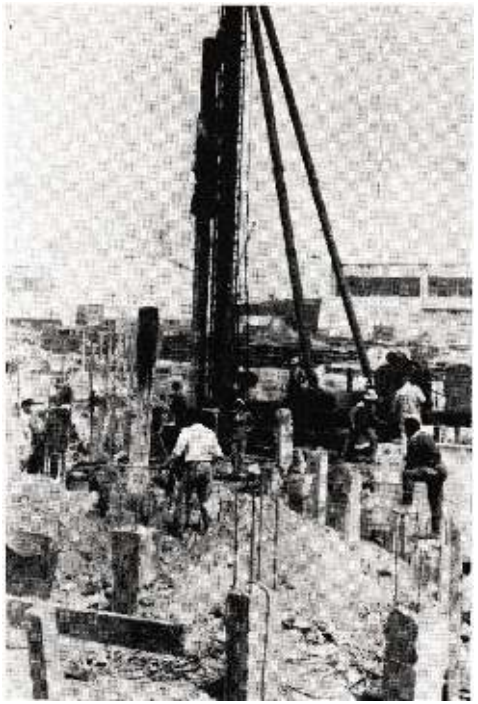
The production of reinforced concrete piles as the first work on the construction site was started by a local company in July 1968. The piles determined by the project were very slender, with a cross-section of 30x30 cm and a length of up to 17 m, reinforced with four ø18 mm bars (see Fig. 5). Objections to excessive slenderness were strictly rejected by the designer. The piles were initially produced in blocks on a flat asphalt road into wooden formwork so that even piles of even rows were pumped into the gaps between the piles of



South block

North block





Z+F IMAGER® 5010X, 3D Laser Scanner

Indoor positioning system and GPS for instant automatic registration in the field

The terrestrial 3d laser scanner Z+F IMAGER® 5010X comes with a unique positioning system which works outdoors and, as an industry-first, also indoors! It will estimate the current position and orientation of the terrestrial 3d scanner to support the registration algorithm to automatically find the correct solution. The scanner will also track your movements while carrying the device on to the next setup and hence provides position estimation for the registration process.

With Z+F LaserControl® Scout and the terrestrial 3D laser scanner Z+F IMAGER® 5010X , Zoller + Fröhlich starts a laser scanning revolution with the Blue Workflow and automatic on-site registration!

Drastically improved WiFi speed and range

Working with the 802.11n-standard and dual antennas, the Z+F IMAGER® 5010X has an increased working range and allows you to communicate and stream scan data quickly to the Scout tablet.

Range up to 187 meters (approx. 600 ft.) of the 3D laser scanner

Due to the wavelength and the approved ranging system, the devices operate within a maximum range of 187 m (approx. 600 ft.).

High-speed up to 1 million pixel/second

With a maximum measurement rate of 1,016,027 pixel/sec the terrestrial laser scanners of Zoller + Fröhlich are one of the fastest in the world.

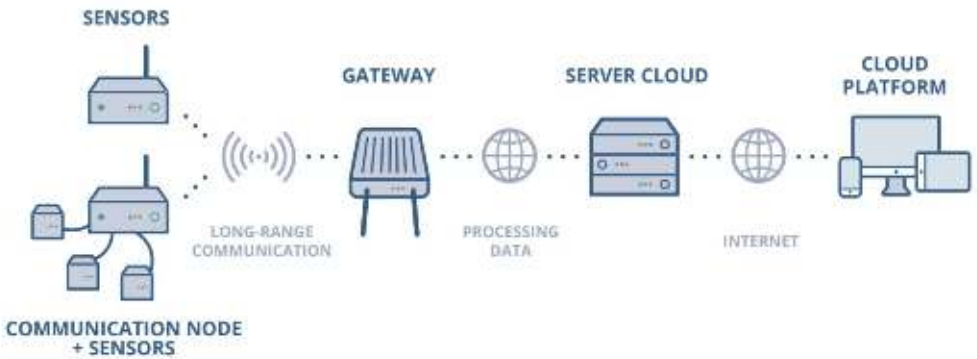
HOW IT WORKS

Move Solutions includes a complete package of wireless devices and a **Web Platform** for data visualization and sensor management.
Once the sensors and system gateways are properly installed on site, they are ready to receive, store and send data.
You can view all this data in real time through a Web interface that allows users to remotely monitor the site or infrastructure. The user can set different parameters for each individual sensor, including sampling rates, resolution, alarm thresholds, activation and much more.

The Move Solutions monitoring system guarantees accuracy, safety and reliability and a significant reduction in overall monitoring costs.

LOGISTICAL - ECONOMIC ADVANTAGES

- Remote monitoring of difficult to access structures
- Ease of installation and use of the system
- Data processing to optimize operations
- Easy addition of sensors to extend the monitored area
- Cost reduction through easy maintenance
- No wiring, saving on installation materials
- Consequent labor savings
- Risk reduction and high reliability



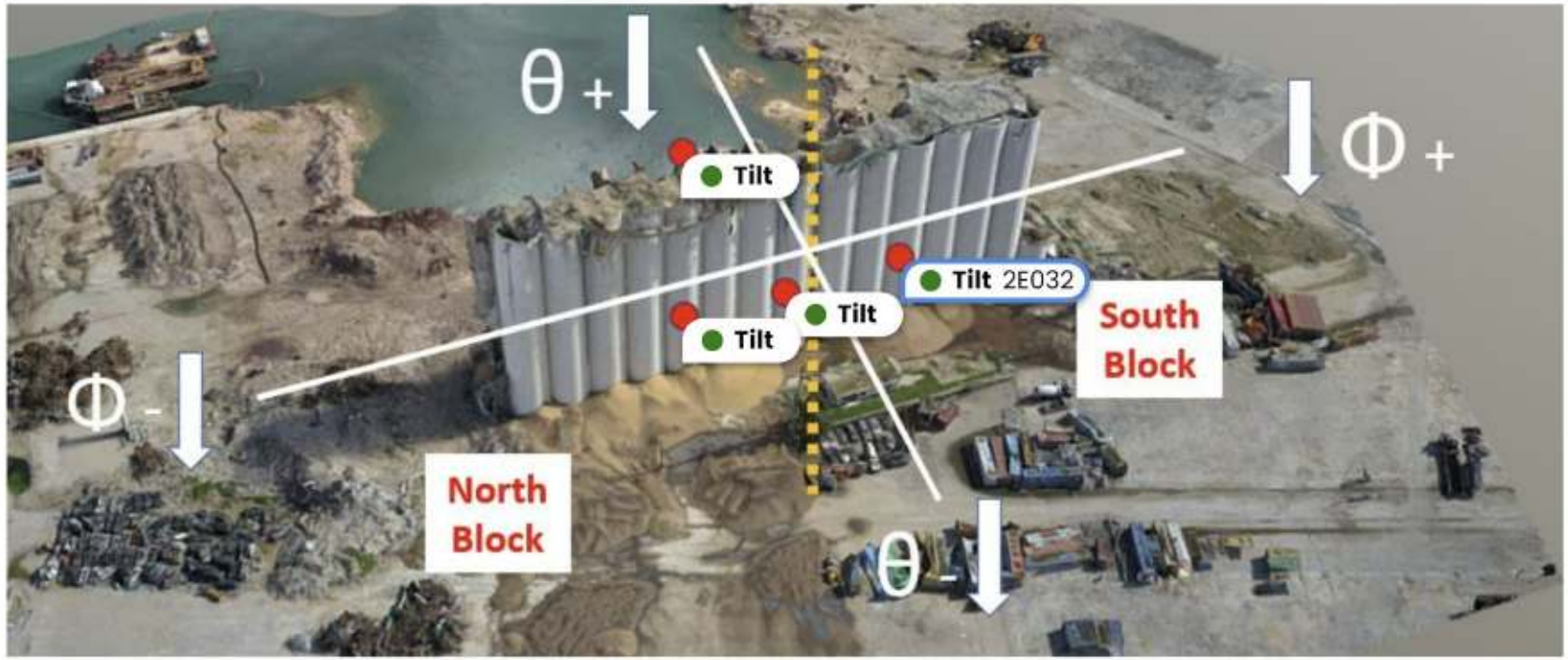
TRIAXIAL TILTMETER

The inclinometer measures the inclination and temperature of the point where it is installed relative to the gravitational axis. By installing a system composed of these sensors it is possible to reconstruct the deformation of the structure. All inclinometers can be perfectly synchronized with each other, perfect for static load tests.
Battery powered and LoRaWAN wireless transmission.
The acquisition methods can be set by the user through the web interface provided in the service.

TECHNICAL SPECIFICATIONS

OPERATION	
Operation with programmed acquisitions	Record of a tilt sample at a fixed rate set by the user (once every 2 minutes, 5 minutes, 15 minutes, 30 minutes). Each sample of inclination is derived from the average of the previous minute. All sensors can be synchronized with each other. Acquisition of the temperature at each event.
Custom Operation Software	It is possible to request custom features that the customer deems necessary for their business.
MEASUREMENT	
Technology	MEMS technology - Triaxial
Acquisition of	- Tilt angle - Temperature
Resolution	0,000015°
Repeatability	±0,0005°
Range	± 90° (on both angles)
Cross Axis Sensitivity	1%
Temperature resolution	0,125°C

BEIRUT PORT SILO



amann

SILO AND 3D EXPERTS

AUB

ETH zürich

USJ
Faculté d'ingénierie

UNIVERSITIES

move

SMARTEC
Via Pobiette 11, CH-6928 Manno, Switzerland

SPECIAL EQUIPMENT ITALY / SWITZERLAND

Very Special Thanks to

the Lebanese Armed Forces,
the Lebanese General Security,
Karantina Fire Brigade,
Lebanon Civil Defence,
the Lebanese Red Cross,
H.E. Amin Salam, Lebanon Minister of Economy and Trade,
the Embassy of Switzerland in Lebanon,
the Beirut Port Silo Team, the Silo Expertise Group,
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