Inhomogeneity as main source of problems in engineering geology

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What is inhomogeneity (or non- homogeneity) :

Inhomogeneity is the spatial variation of

ground material properties

or

ground mass properties.

What is inhomogeneity (2):

For example:

- an intact rock strength variation within a block of intact rock material causes the intact rock material to be inhomogeneous
- a variation in porosity in a clay causes a clay layer to be inhomogeneous
- a variation in the orientation of discontinuities (e.g. jointing) causes a rock or soil mass to be inhomogeneous

What is inhomogeneity (3):

- Inhomogeneity results in new boundaries in the ground mass (which may also be geological layer boundaries).
- These boundaries will coincide with a geotechnical unit boundary.
- A gradual change in a property leads theoretically to an unlimited number of boundaries.

Why is inhomogeneity (or non- homogeneity) a source of problems in engineering geology:

because:

- difficult to determine
- difficult to handle

Why is inhomogeneity of importance in engineering geology:

If homogeneity is poorly determined or poorly handled consequences can be large for the civil engineering application that is to be built on or in the subsurface

What is meant by homogeneity in engineering geology:

Any design of an application of the subsurface depends on the division in "**homogeneous**" units; the geotechnical units

Geotechnical unit:

A “geotechnical unit” is a unit in which the geotechnical properties are the same.

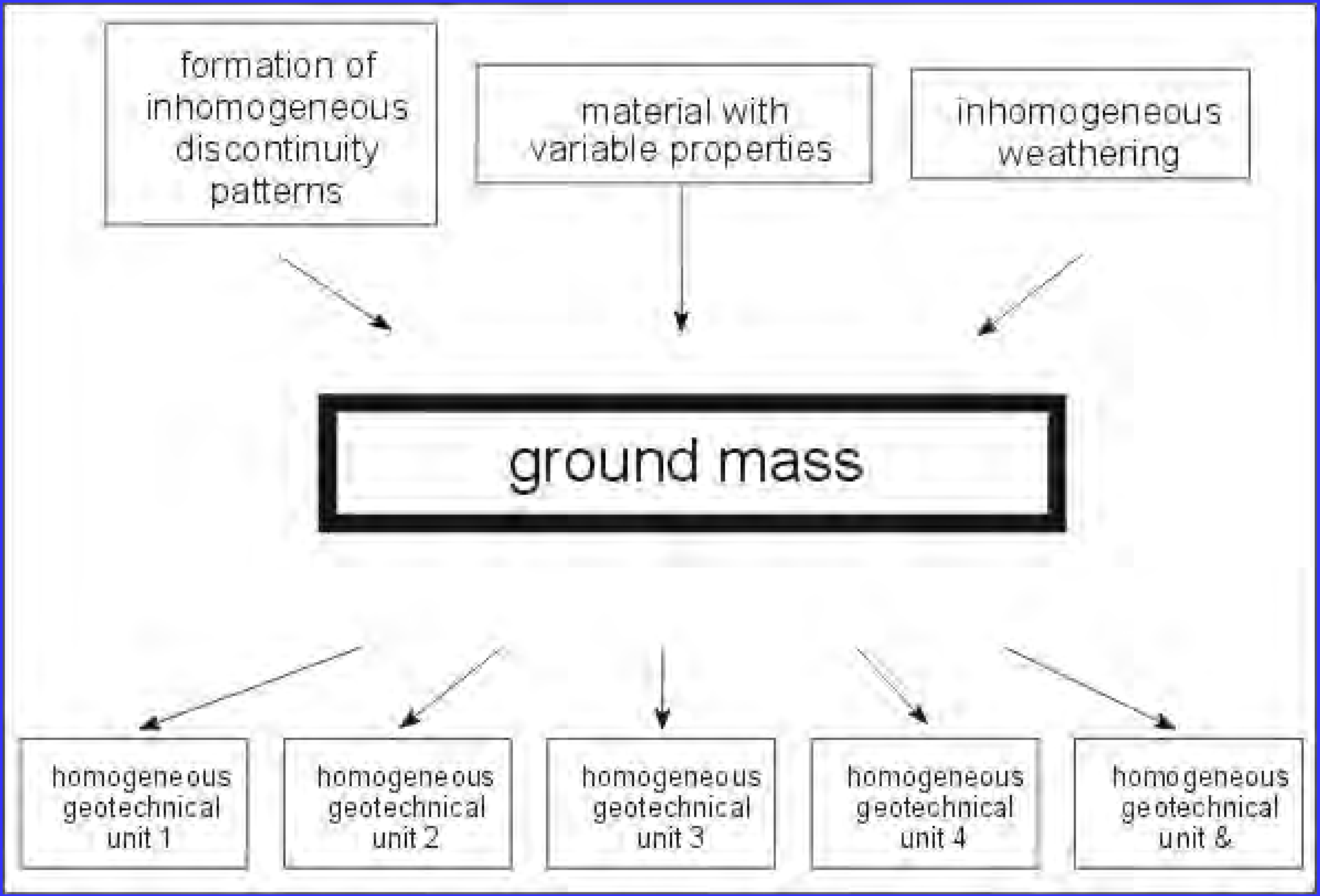
Geotechnical units with homogeneous properties are required to make a calculation, determine design parameters, etc.

A second problem:

Mostly we cannot see what is inhomogeneous and where it is

(it is somewhere in the subsurface, covered by another material)

geotechnical units are based on the experience and expertise of the engineering geologist



“No geotechnical unit is really homogene….”

A certain amount of variation has to be allowed as otherwise the number of units will be unlimited

“The allowable variation of the properties within one geotechnical unit depends on:

1) the degree of variability of the properties within a mass,
2) the influence of the differences on engineering behavior, and
3) the context in which the geotechnical unit is used.

“A ground mass containing a large variation of properties over a small distance necessarily results in geotechnical units containing larger variations in properties

This is because it is impossible or too costly to establish with sufficient accuracy all boundaries between the various areas with different properties within the mass.

Smaller allowed variability of the properties in a geotechnical unit results in:

- higher accuracy of geotechnical calculations
- less risk that a calculation or design is wrong

Smaller allowed variability of the properties in a geotechnical unit

- requires collecting more data and is thus more costly
- geotechnical calculations are more complicated and complex, and cost more time

Higher accuracy obtained for a calculation based on more data has to be balanced against the economic and environmental value of the engineering structure to be built and the possible risks for the engineering structure, environment, or human life.

Hence:

- the variations allowed within a geotechnical unit for the foundation of a highly sensitive engineering structure (for example, a nuclear power station) is smaller

- the variations allowed within a geotechnical unit in a calculation for the foundation of a standard house will be larger

No standard rules are available for the division of a mass into geotechnical units and this transformation depends on experience and ‘engineering judgment’. However, features such as changes in lithology, faults, shear zones, etc., are often the boundaries of a geotechnical unit

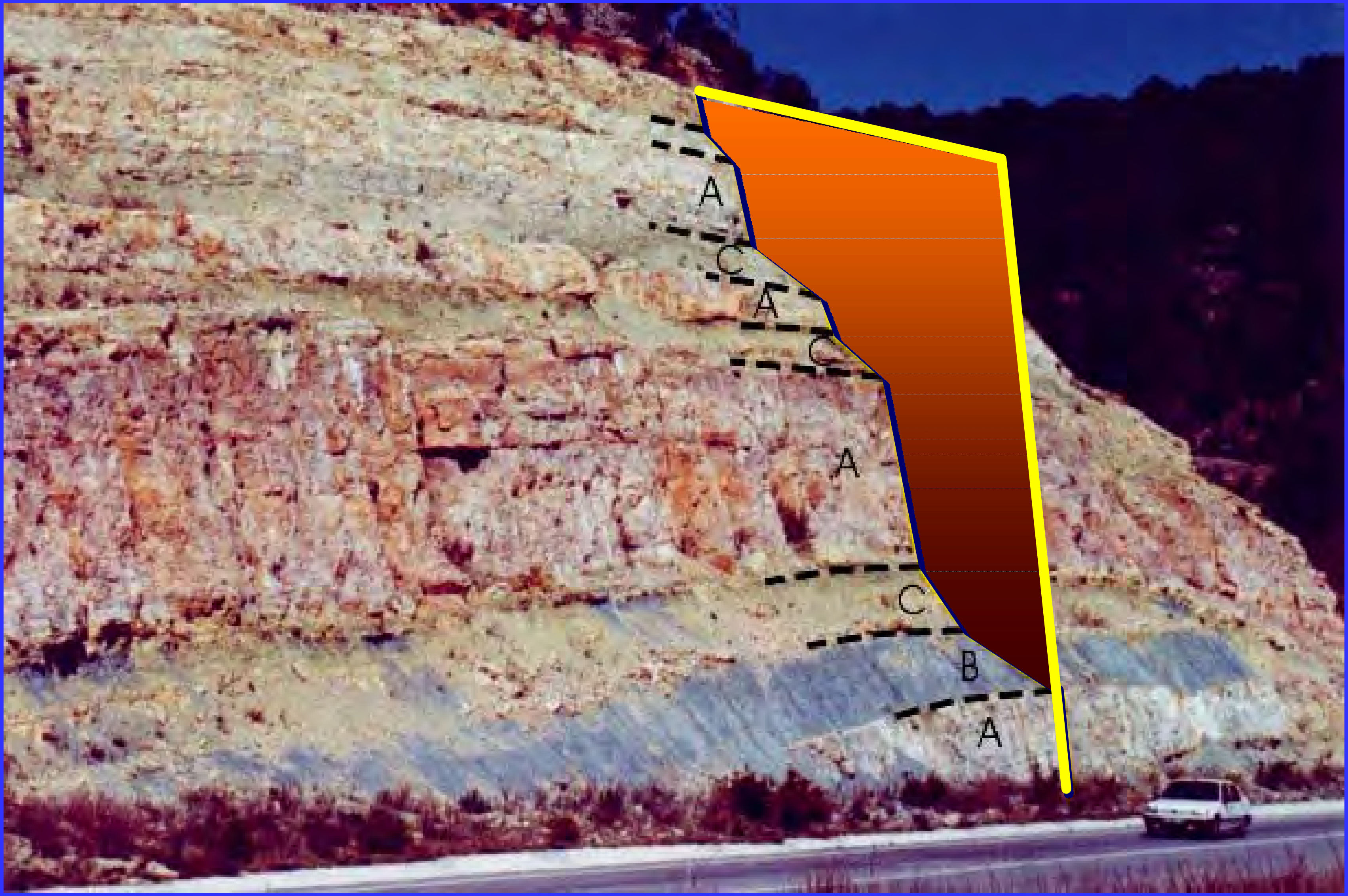
Example 1 (1)

What are the implications if wrong

Example 1: What are the implications if wrong (2): Original situation

Example 1: What are the implications if wrong (3): final slope?

Example 1: What are the implications if wrong (4): design error



Example 2: Many discontinuity sets with much variation in orientation (too many for the design engineer?)

Example 3: Many discontinuity sets with much variation in orientation (too many for the design engineer?)

Example 4: Variation in clay content in intact rock causes differential weathering

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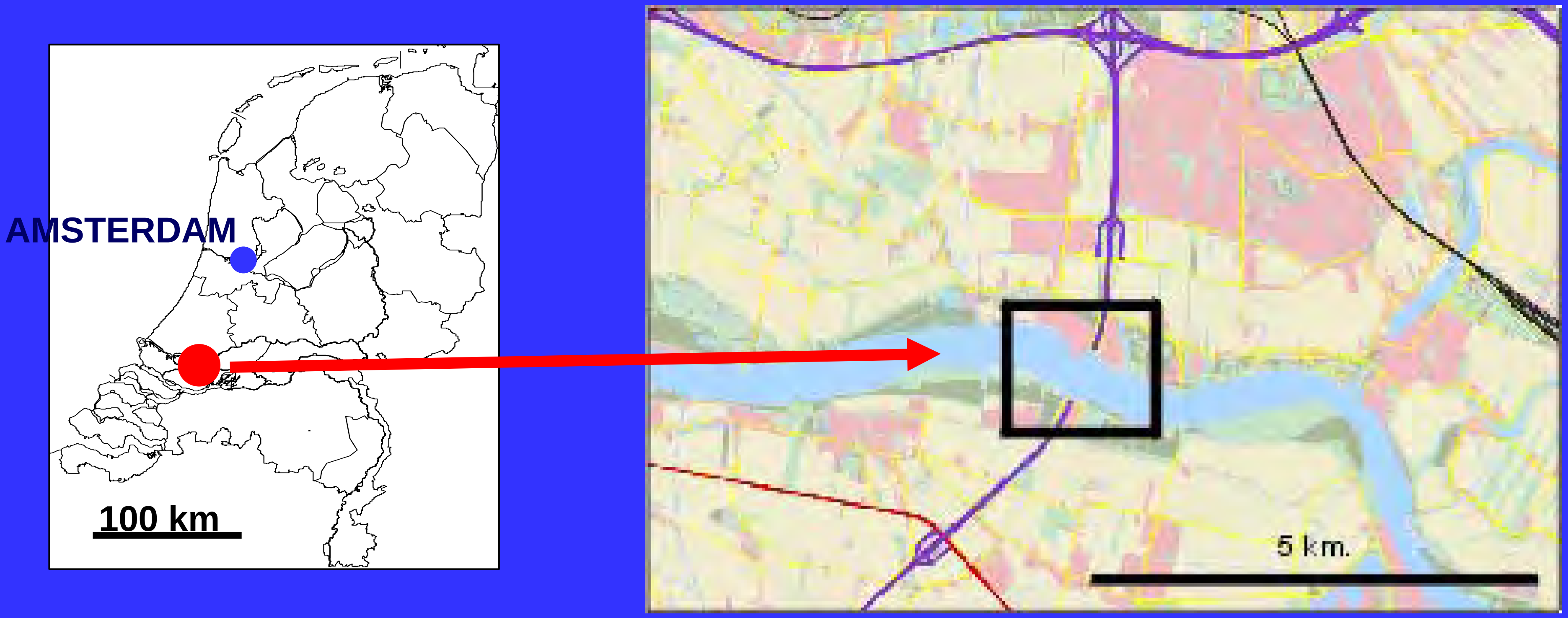
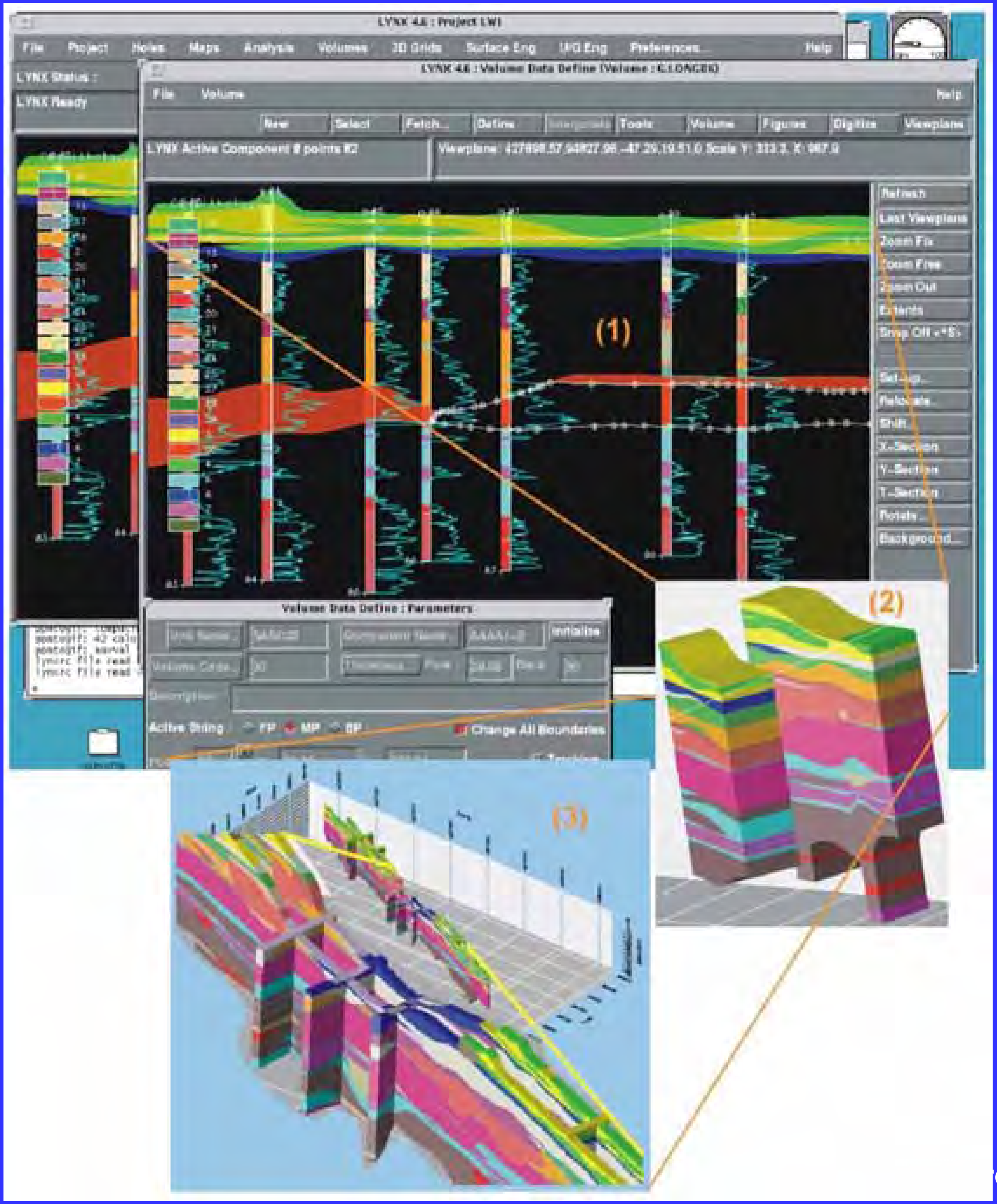
Example 5

What can go wrong if the geological model is too much simplified with too few units

Heinenoord tunnel

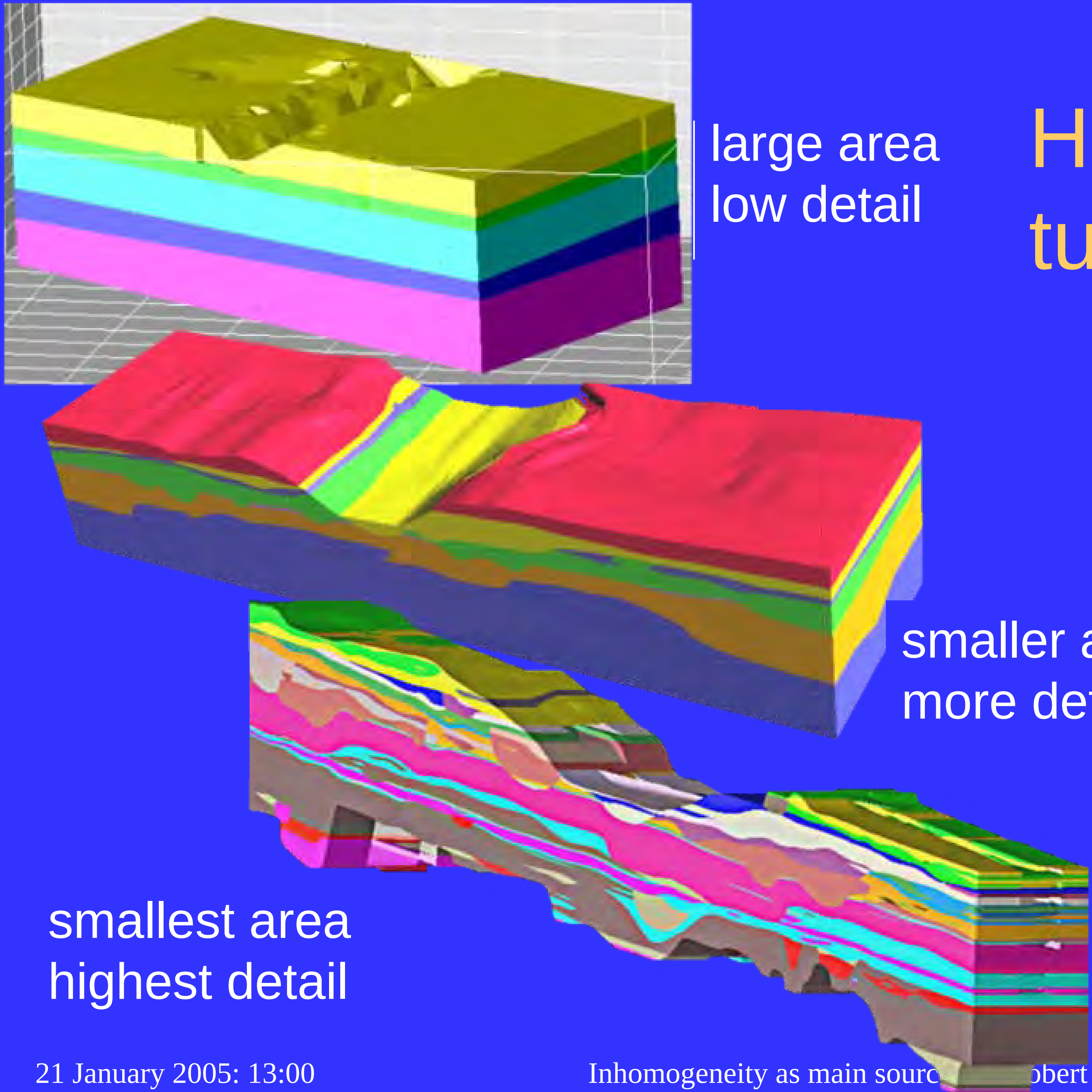
(balanced earth pressure shield bored tunnel in soft sediments near Rotterdam, Netherlands)





Heinenoord tunnel (2)

Heinenoord tunnel (3)



large area
low detail

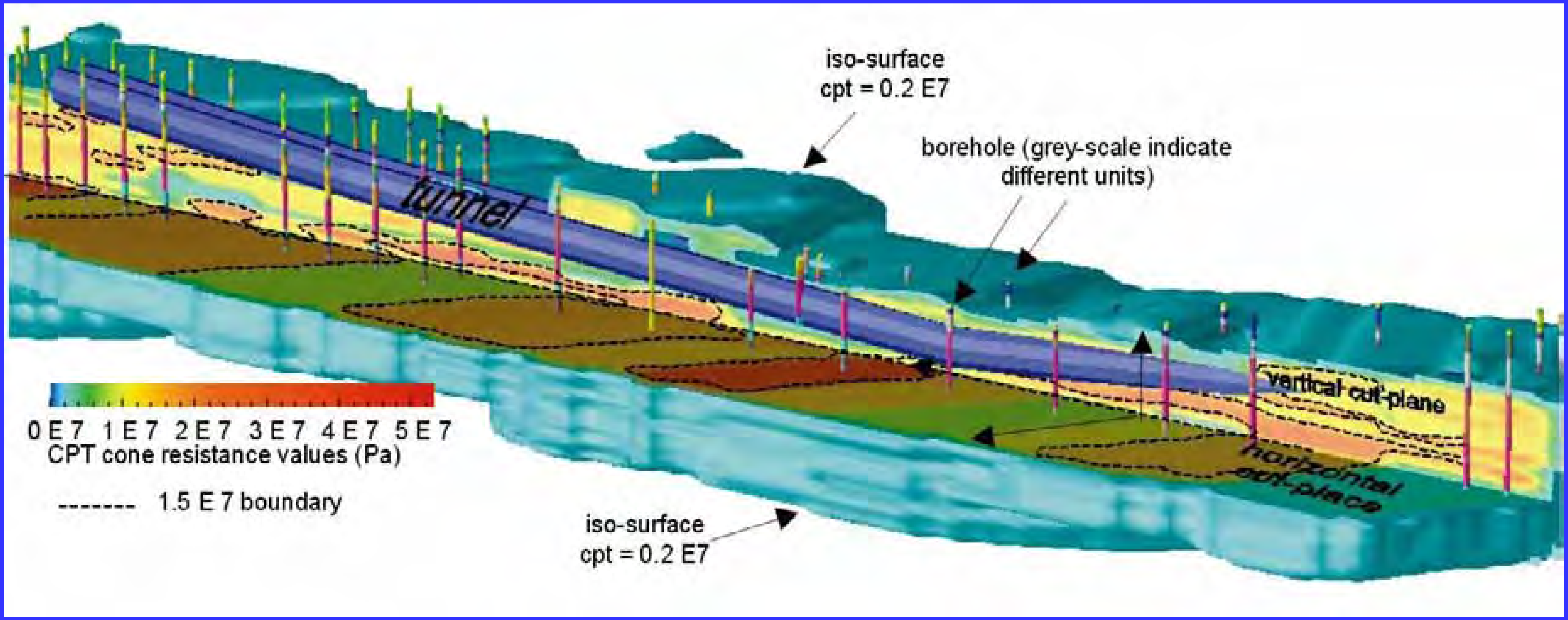
smaller area
more detail

smallest area
highest detail

Each color indicates a different layer with different material, properties, etc.

Heinenoord tunnel (4)

Strength (Cone Penetration Test) model



(Heinenoord Tunnel, Netherlands)

Heinenoord tunnel (5)

- Very detailed geology model was made **after** the tunnel was finished.
- Subsurface geology model used for design consisted of a simplified model with 4 different units because the calculation model became too complex if more different layers were used

Heinenoord tunnel (6)

- Major problems during construction due to blow outs
- Project delayed by many months
- Difficult to prove but problems with boring such as blow outs, would probably have been anticipated if not a too rigorously simplified subsurface model was used

Many more examples can be given of civil engineering structures in rock or soil masses that resulted in problems because:

- variation in properties was not recognized
- variation was not incorporated properly in geotechnical calculations

What could be done ?

- more data
- do more with the data

More data:

Simple to state, but nobody is prepared to pay for it;

hence,

It should not just be more data of the same (boreholes, penetration tests, etc.), but data that gives a considerably large added value for quantification of homogeneity against limited costs to obtain the data

More data:

for example:

- remote sensing techniques
- geophysics

More data:

Lidar from surface, air or space

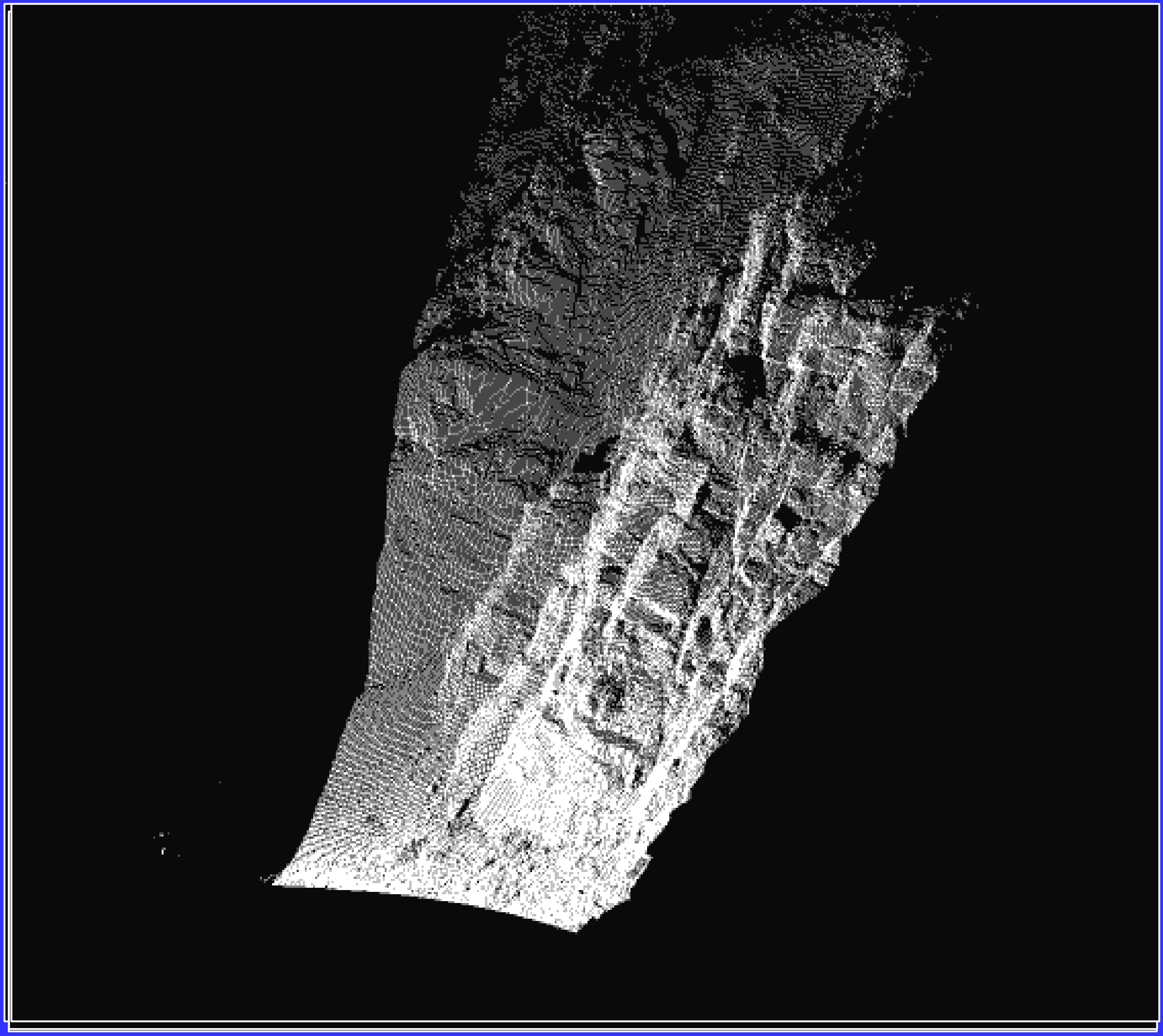
Rock face - Mt. Vernon (Co.), USA

(After Slob et al., 2002)

Rock surface scan

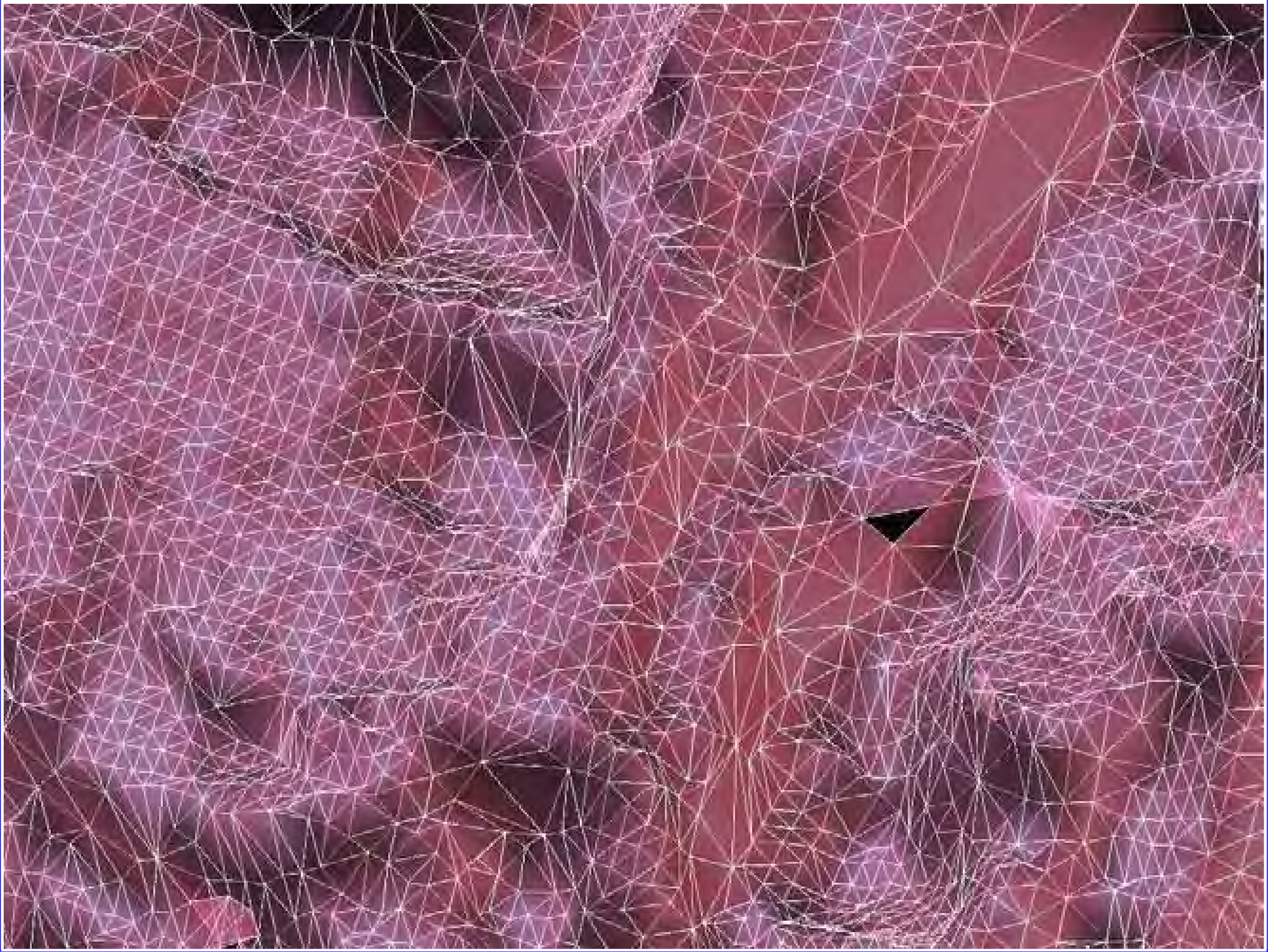
(After Slob et al., 2002)

Visualization of point cloud data



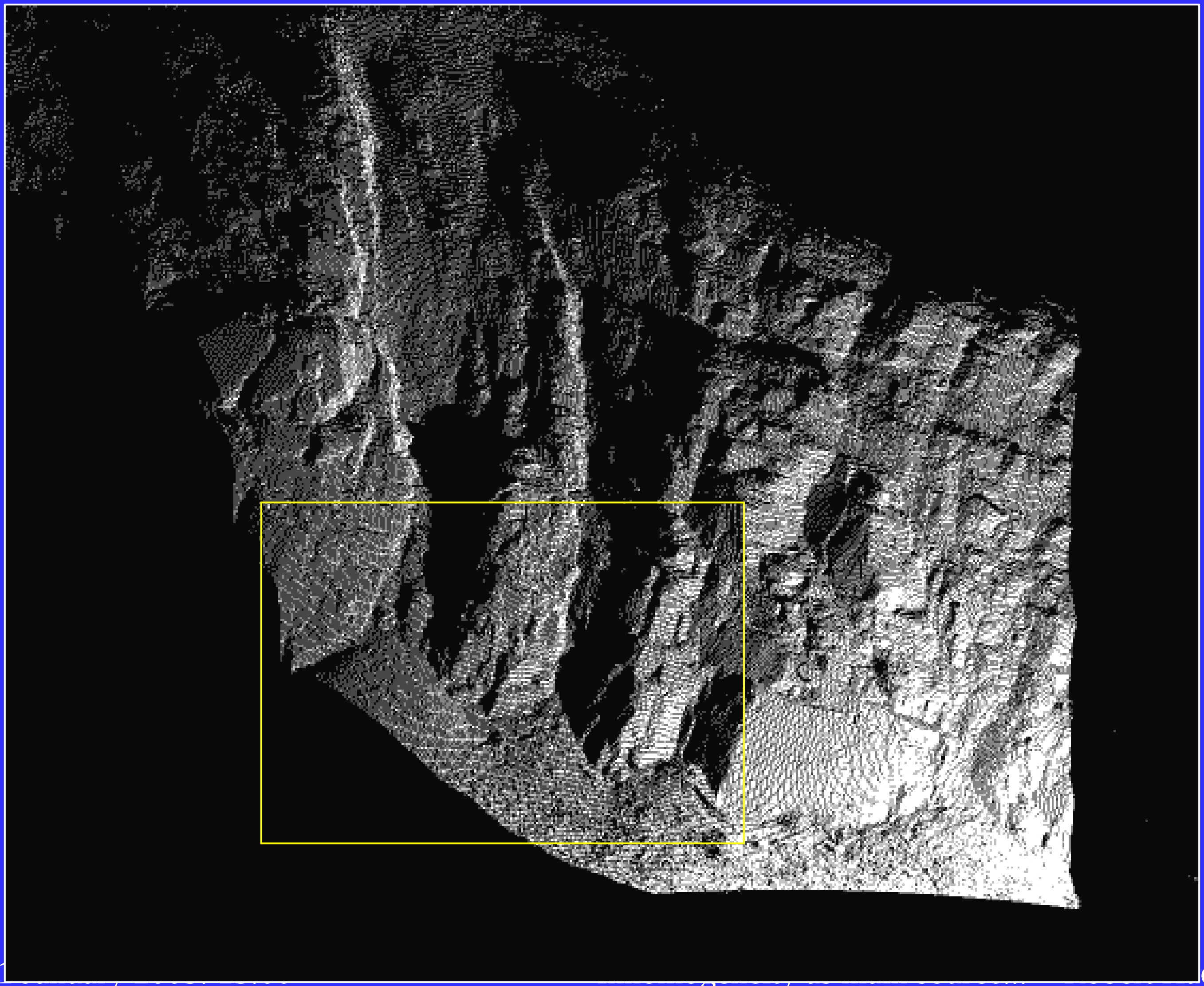
(After Slob et al., 2002)

3D Delaunay triangulation to create surface through point cloud data



(After Slob et al., 2002)

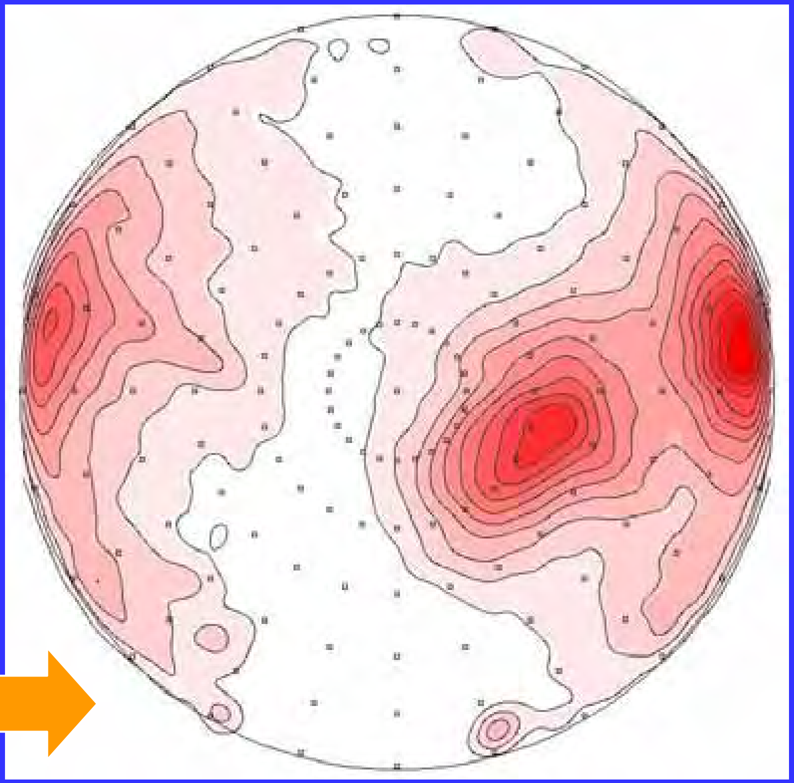
Trial on sub-dataset



Statistic analysis of triangulated data

Digitally rendered 3d model

(After Slob et al., 2002)

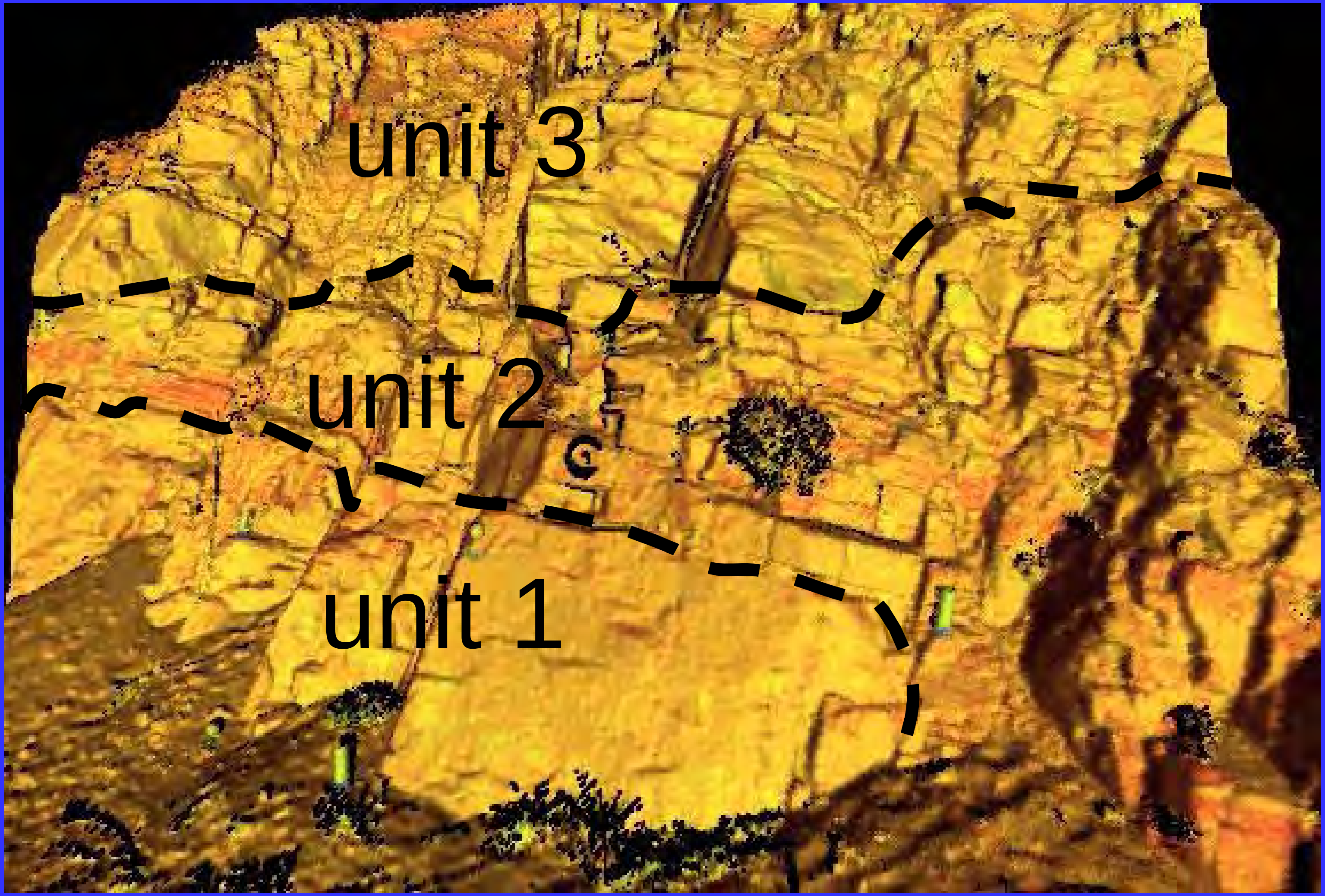


Kernel density pole plot of all triangle orientations of this part of rock surface

Homogeneity and division in geotechnical units

can homogeneity and division in geotechnical units be defined by an automatic procedure , e.g. for example Lidar

Division in geotechnical units



What can be expected from Lidar?

- Orientation discontinuity sets with variation
- Spacing of discontinuity sets with variation
- Large scale discontinuity roughness with variation
- Infill?
- Division in geotechnical units?

More data:

Geophysics

Very promising developments in

- Resistivity imaging
- Possibly shear wave seismics

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Geophysics

Very promising developments in

- Resistivity imaging
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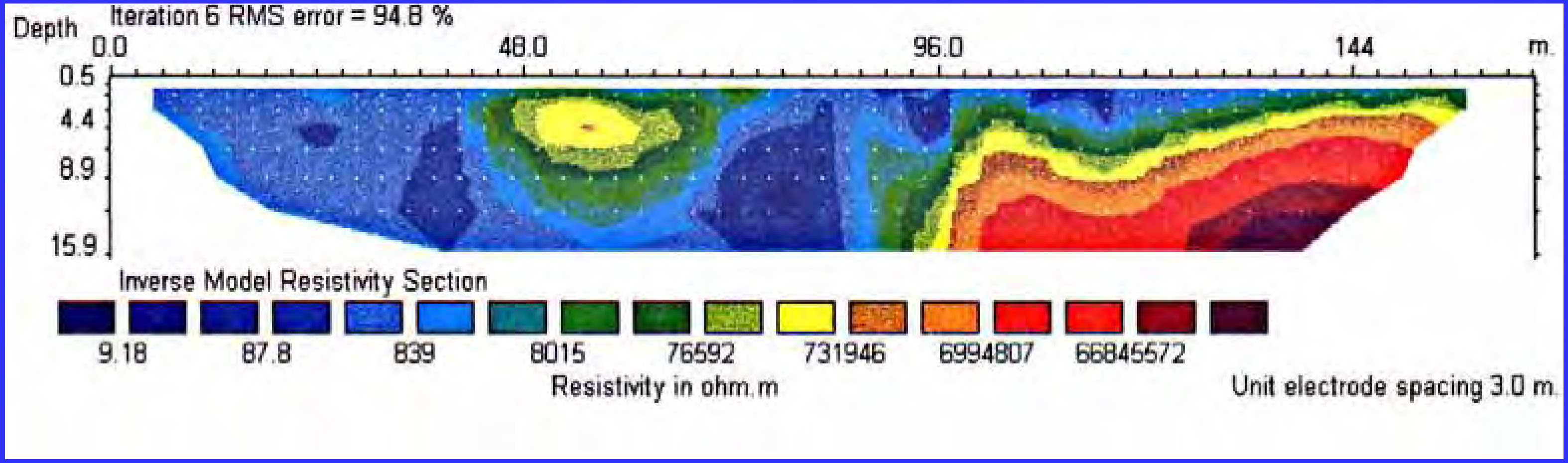
Resistivity 2D imaging



Shear wave high frequency vibro seismics

What to be expected?

- Recognition of individual discontinuity sets?
- Shear stiffness of intact material & discontinuities?
- Material properties in more detail than at present
- Karst (with a far better resolution than at present)

Do more with the already existing data

incorporate probabilities with data

and

express results in terms of likelihood

Rock mass classification systems

Inhomogeneity is inherently incorporated in classification system (because empirically based on real data of “inhomogneous” masses)

Rock mass classification systems

However, most systems to do give result in terms of likelihood, but use an absolute figure;

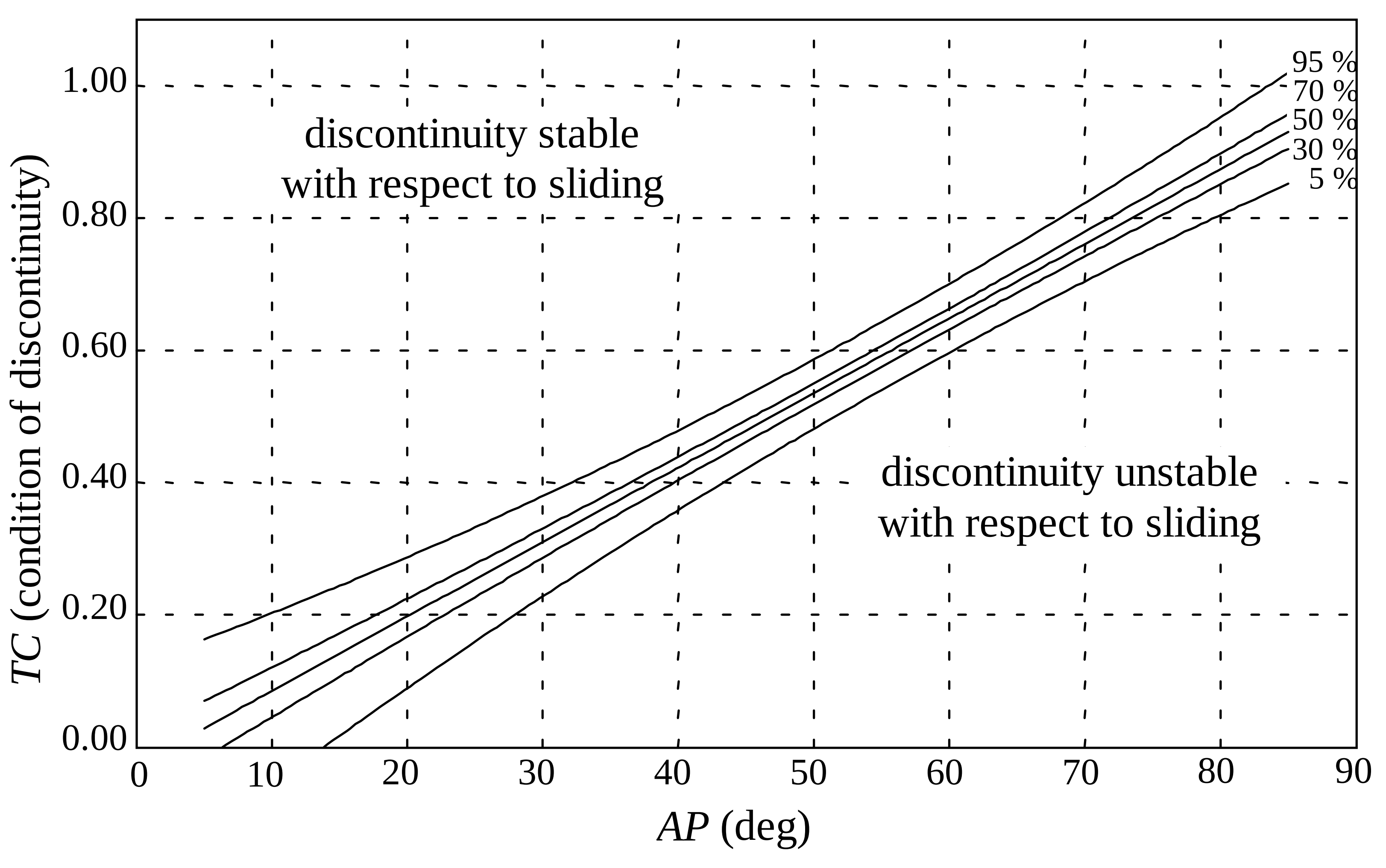
e.g. these lost (do not report) the additional information on inhomogeneity

Example Slope Stability Classification System (SSPC)

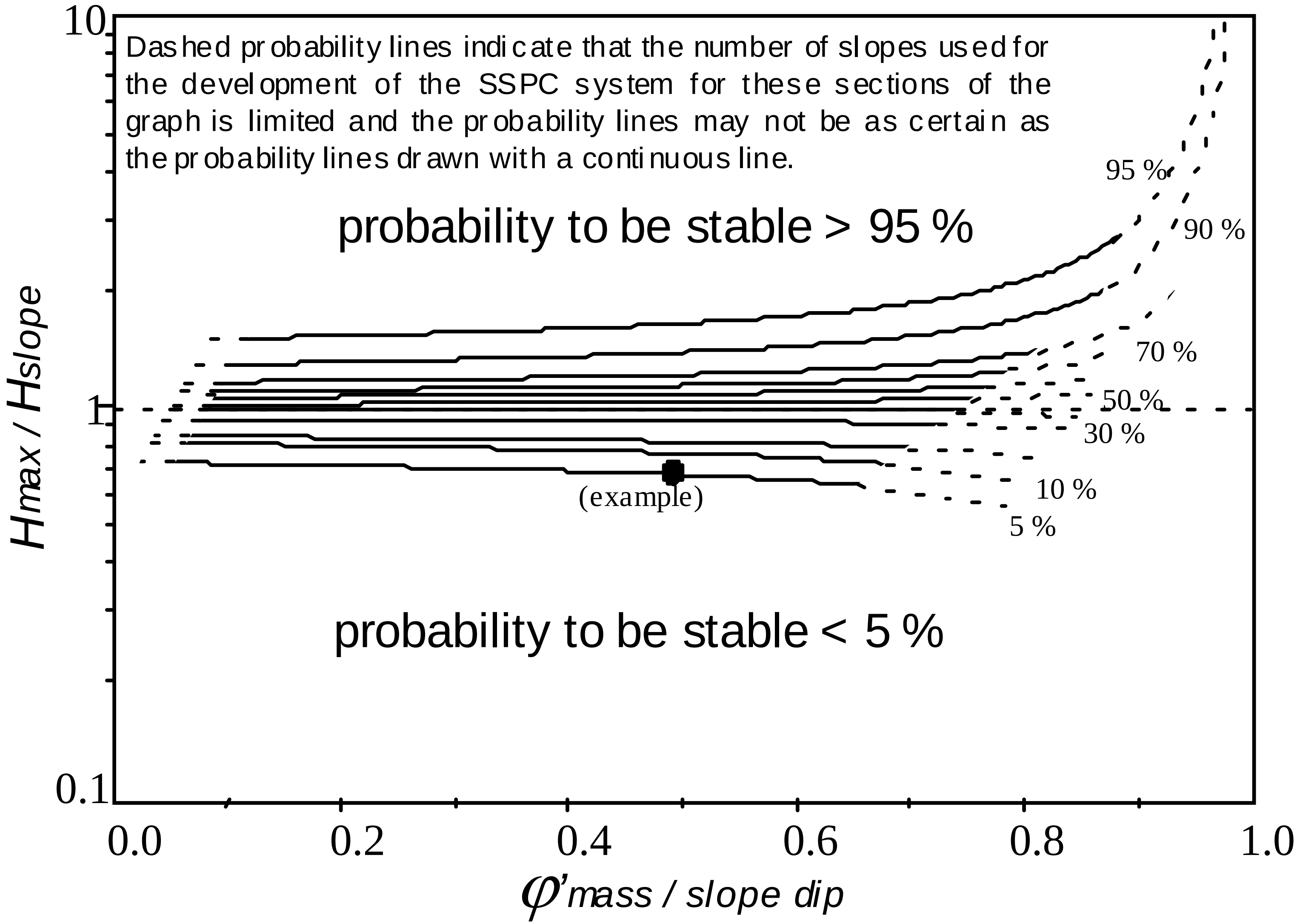
Empirically based on real slopes, hence probability incorporated in data,

But also gives result in terms of likelihood

Sliding probability



Probability orientation independent failure



Poorly blasted slope

Poorly blasted slope

General impression: extremely poor. The stability of the new road cut with a height of 13.8 m, with a degree of rock mass weathering of 'moderately' and 'dislodged blocks' due to blasting, results in a stability assessment of about 8 % for a slope dip of 70° in 1996. This is in agreement with the visual observed stability at that time. The rock mass is clearly not able to support a slope with a dip of 70°. According to the SSPC system, stability will be achieved if the slope dip is decreased to about 45°. In 2003 the slope dip had been reduced to about 50-55° and visually assessed the slope is still unstable.

If such a slope had been properly designed using the SSPC system: the recommended slope dip would have been 40 ° with a probability to be stable of about 75%

Quantify risk (or likelihood) of subsurface models

Two items:

a) Data itself – relatively easy (e.g. statistics)

b) Expert knowledge (“expertise”) used for interpreting the data – difficult

How do we know the subsurface?

From:

- Point views (boreholes)
- Some indirect measuring methods on physical properties of the ground (for example, geophysics)

The point views (boreholes) and indirect physical properties of the ground are interpreted to obtain a model of the subsurface

The interpretation is the weak angle

A geologist or engineer interprets based on her/his expert knowledge, a model of the subsurface

Hence, the interpretation is always uncertain

How good was the expert knowledge?

and

if the knowledge was perfect then still mostly many interpretations are possible

The subsurface may be a Lasagna, but it is uncertain what it contains

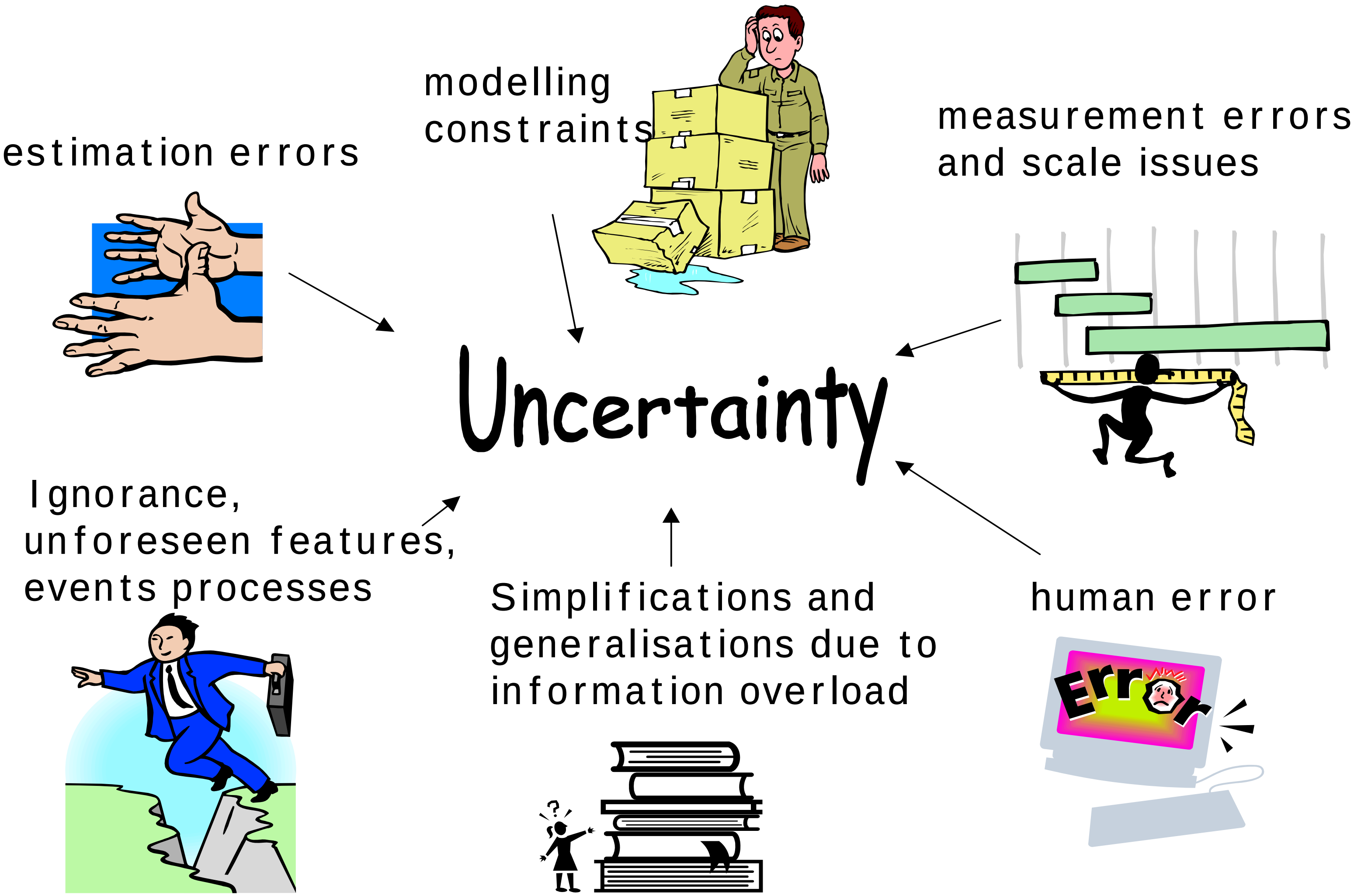
(De Mulder, 2003)

(in restaurants that often seems the case too)

How to solve this problem?

And can it be solved or controlled?

Uncertainty of Model



Two examples of preliminary research results:

Regional Scale: sparse data - poor quality of resulting 3d model – example North Sea Seafloor Pipeline project

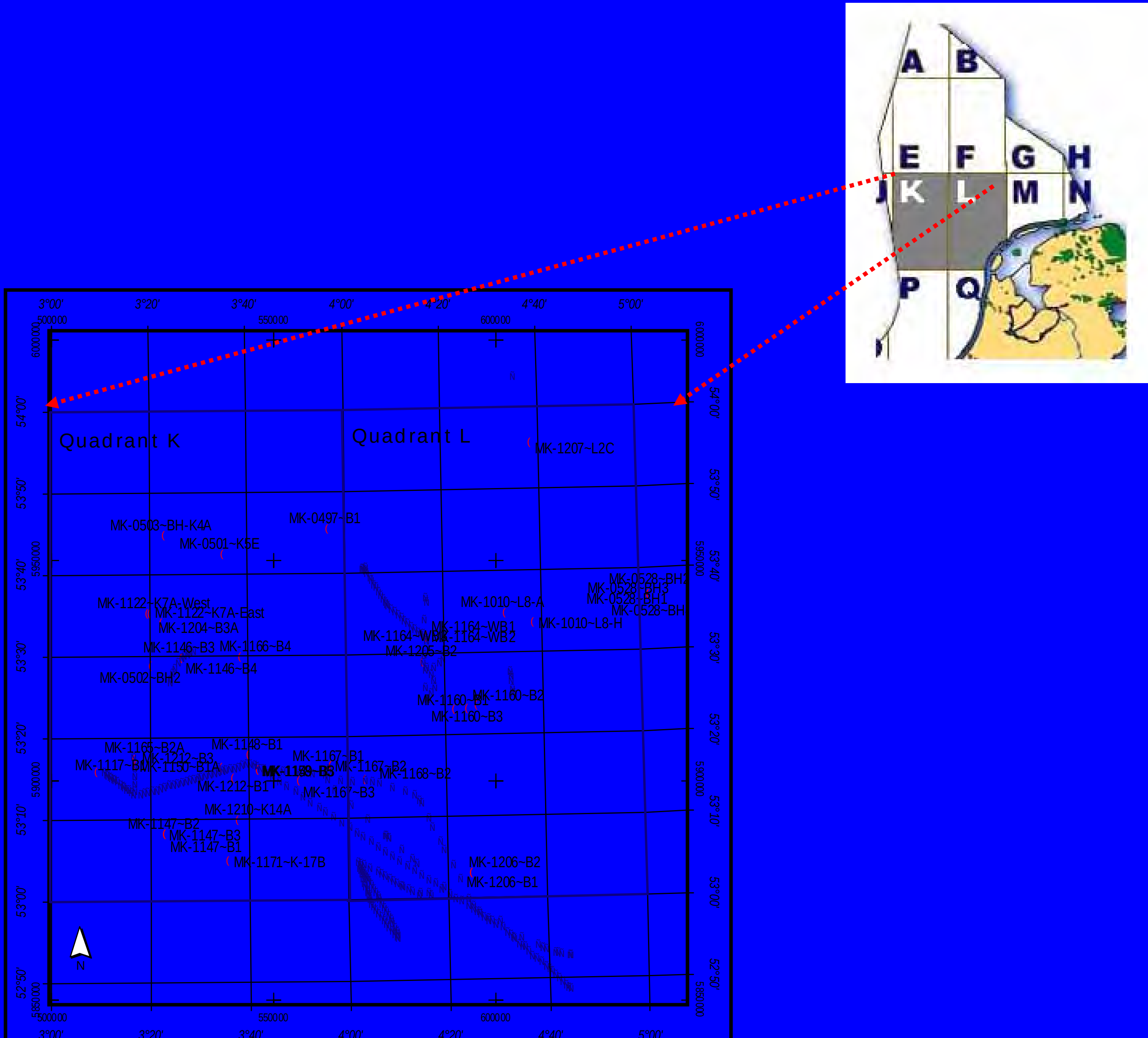
Site Scale: dense data – good quality of resulting 3d model – example Reeuwijk Road

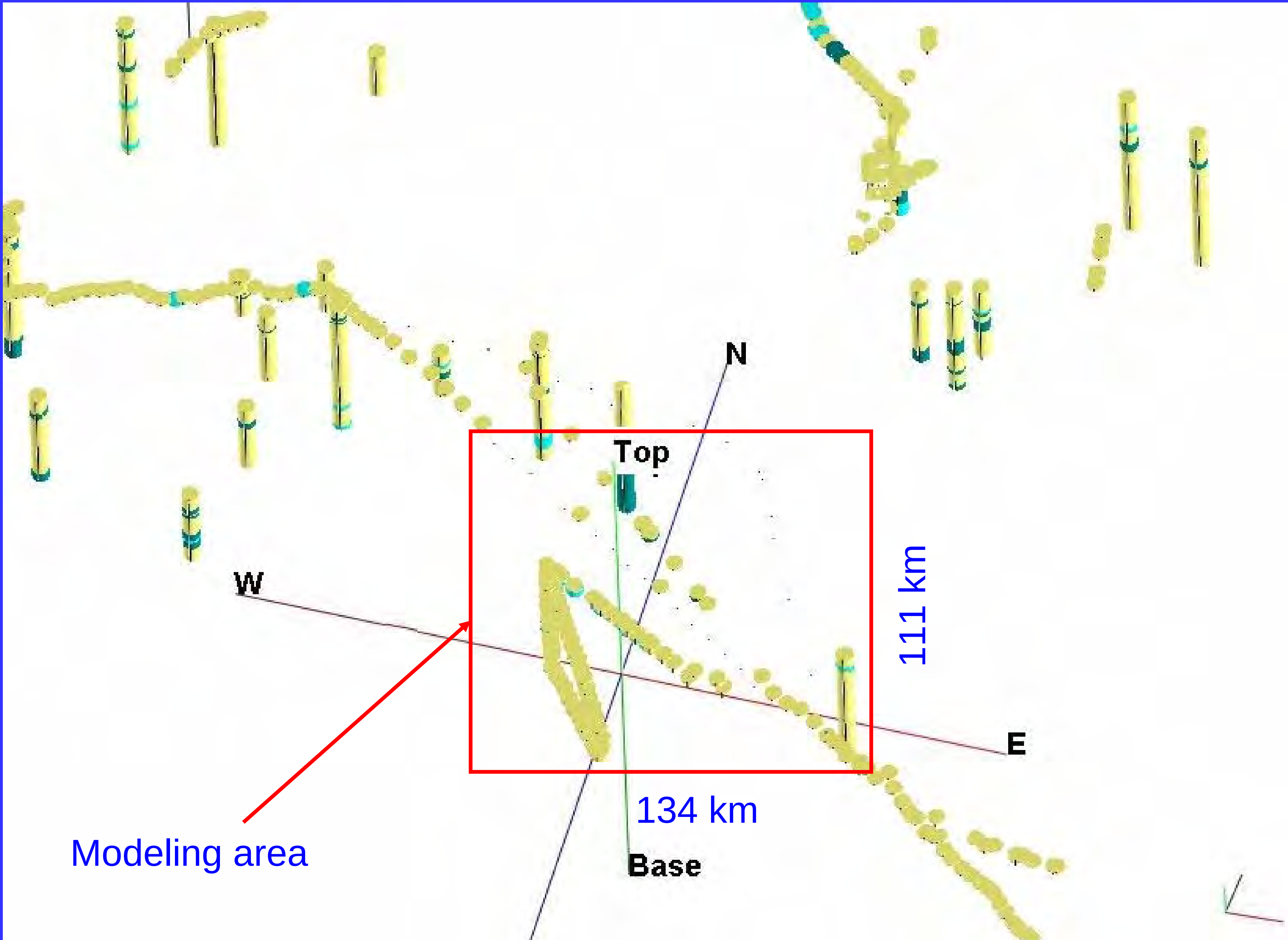
North Sea Seafloor Pipeline project

Project question:

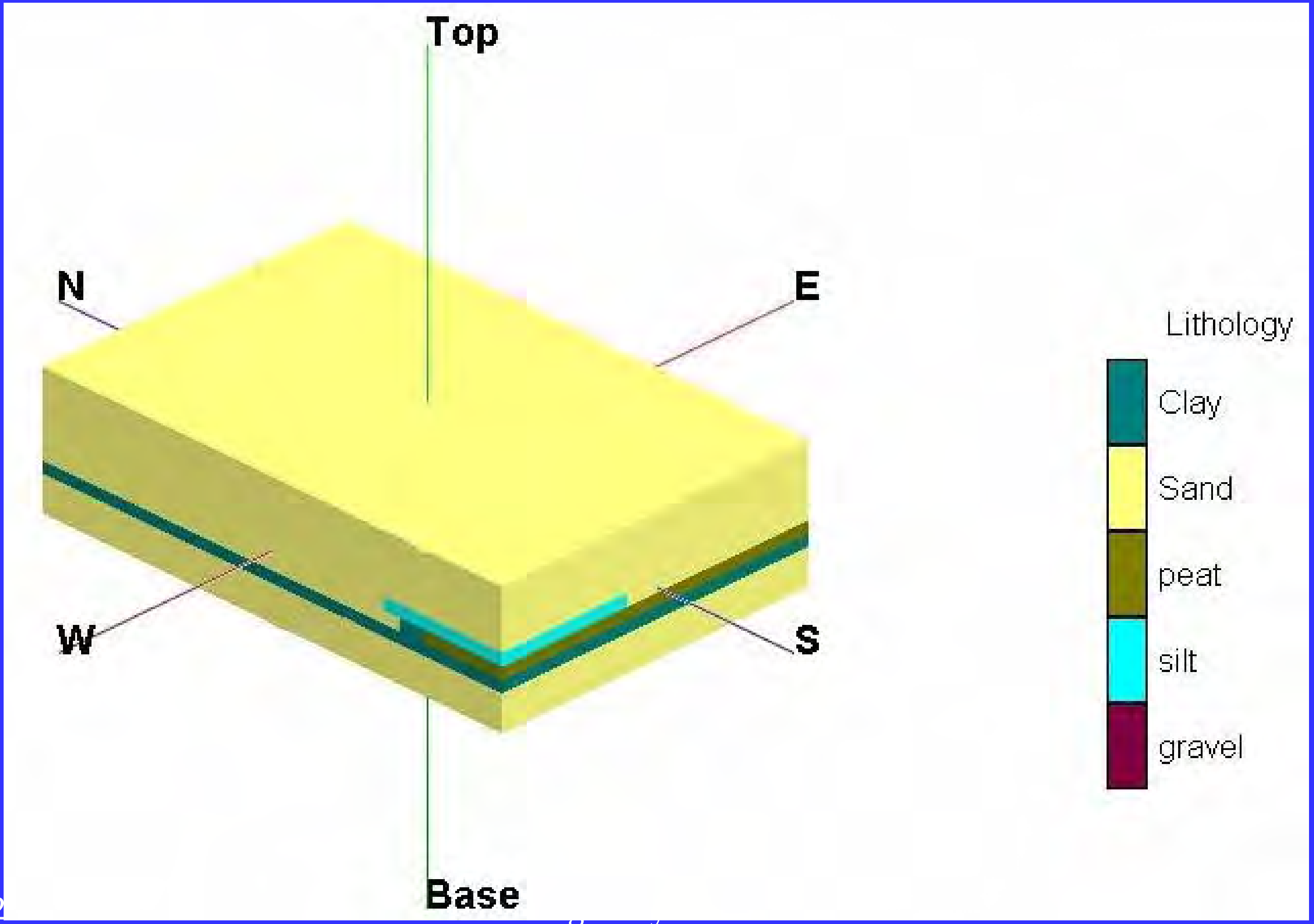
how much sand is available to bury the pipeline in, and how reliable is this thickness

- 340 shallow and deep holes that cover an area of about 15000 km^2 (134 km × 111km)
- drilling grid is irregular, but with most of the holes drilled along the design routing of the pipeline


A
B
E
F
G
H
J
K
L
M
N
P
Q
Quadrant K
Quadrant L
3°00'
3°20'
3°40'
4°00'
4°20'
4°40'
5°00'
54°00'
53°50'
53°40'
53°30'
53°20'
53°10'
53°00'
52°50'
MK-1207~L2C
MK-0497~B1
MK-0503~BH-K4A
MK-0501~K5E
MK-1122~K7A-West
MK-1122~K7A-East
MK-1204~B3A
MK-1146~B3
MK-1166~B4
MK-1146~B4
MK-0502~BH2
MK-1010~L8-A
MK-1010~L8-H
MK-1164~WB1
MK-1164~WB2
MK-1205~B2
MK-0528~BH2
MK-0528~BH1
MK-1160~B1
MK-1160~B2
MK-1160~B3
MK-1165~B2A
MK-1148~B1
MK-1117~B1
MK-1212~B3
MK-1150~B1A
MK-1167~B1
MK-1167~B2
MK-1168~B2
MK-1212~B1
MK-1167~B3
MK-1210~K14A
MK-1147~B2
MK-1147~B3
MK-1147~B1
MK-1171~K-17B
MK-1206~B2
MK-1206~B1
N
Shallow holes
Deep holes
Metres

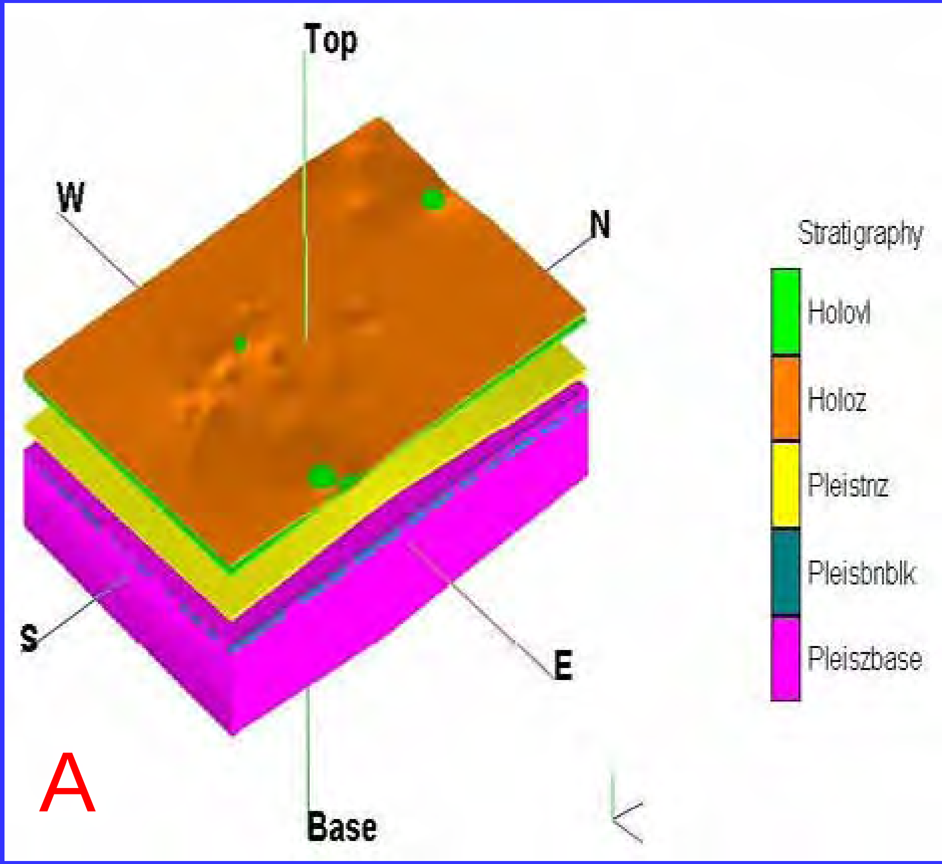

N
Top
W
111 km
E
134 km
Modeling area
Base

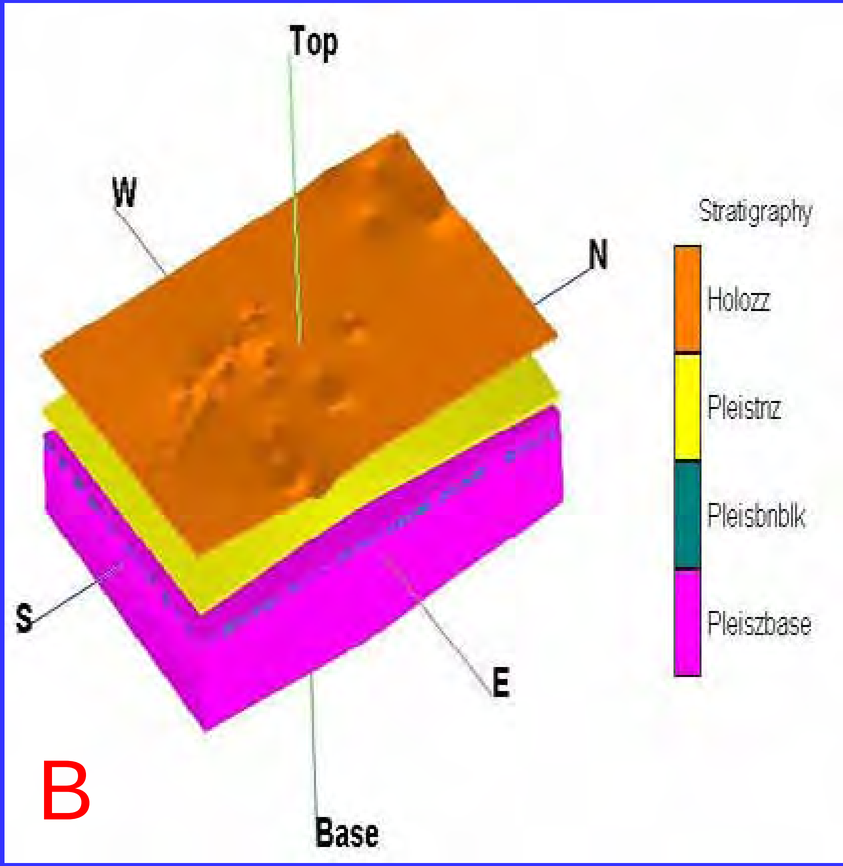
A part of the area (40 km × 26 km = 400 km^2) with 80 shallow and 2 deep boreholes (3D Lithological Model)



Model A: five units

Model B: four units





Conclusion pipeline project

More data will virtually not add to the quality of the required data, e.g. the sand cover thickness,

and

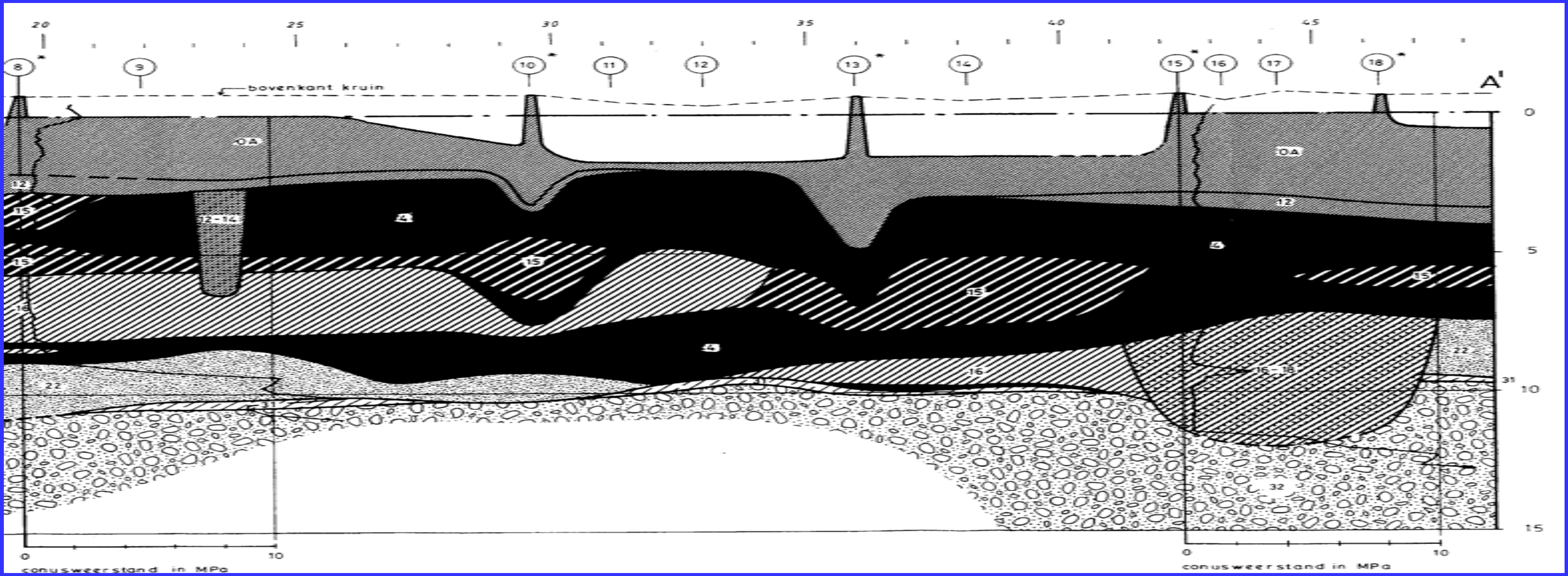
More data will only marginally improve the reliability of the data

Case Study – Reeuwijk Road Project

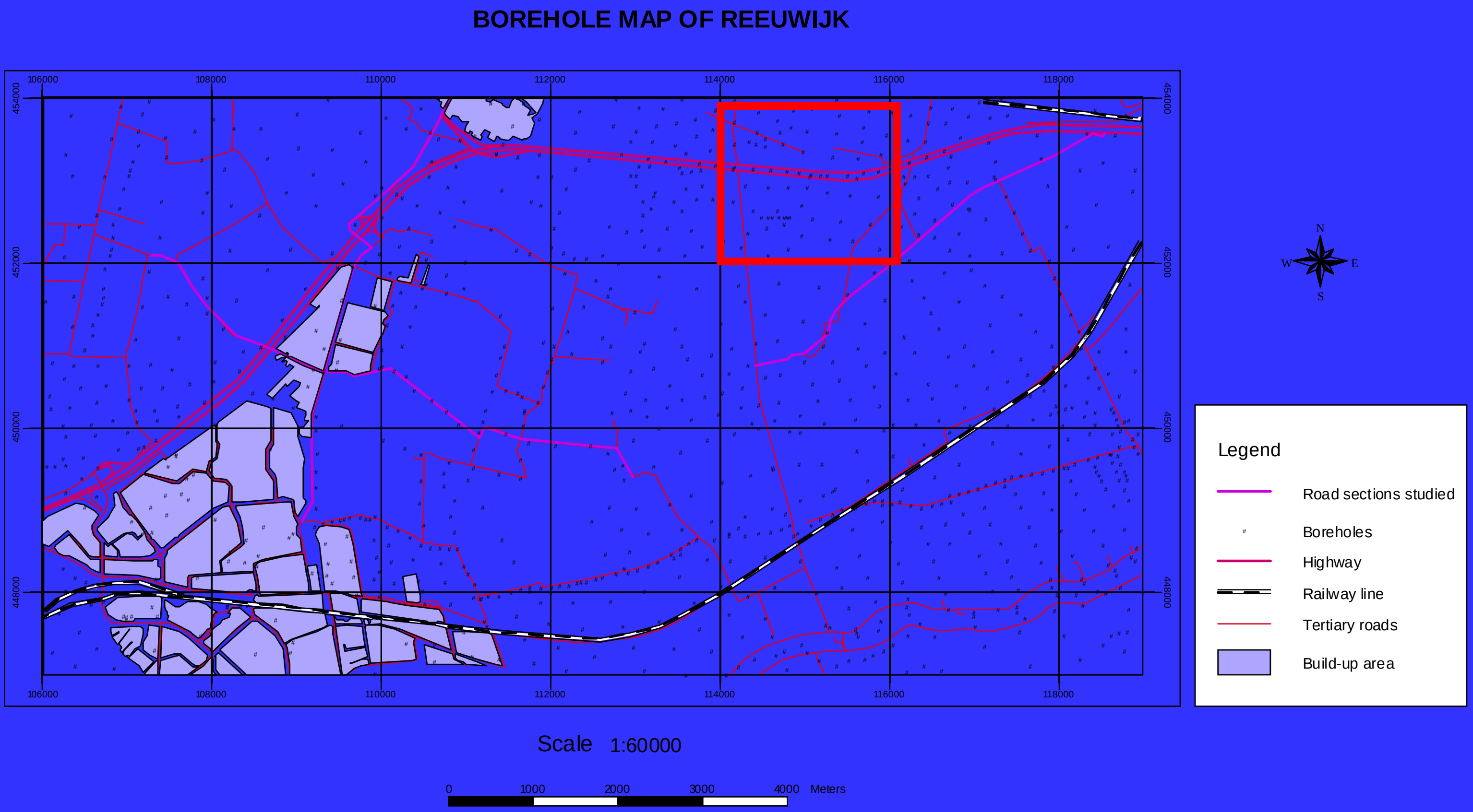
Project question: how much settlement can be expected for a road alignment

(Reeuwijk area in the Western part of the Netherlands is known for extensive layers of peat that can give excessive amounts of settlement)

Interpreted model available from geological survey of the Netherlands

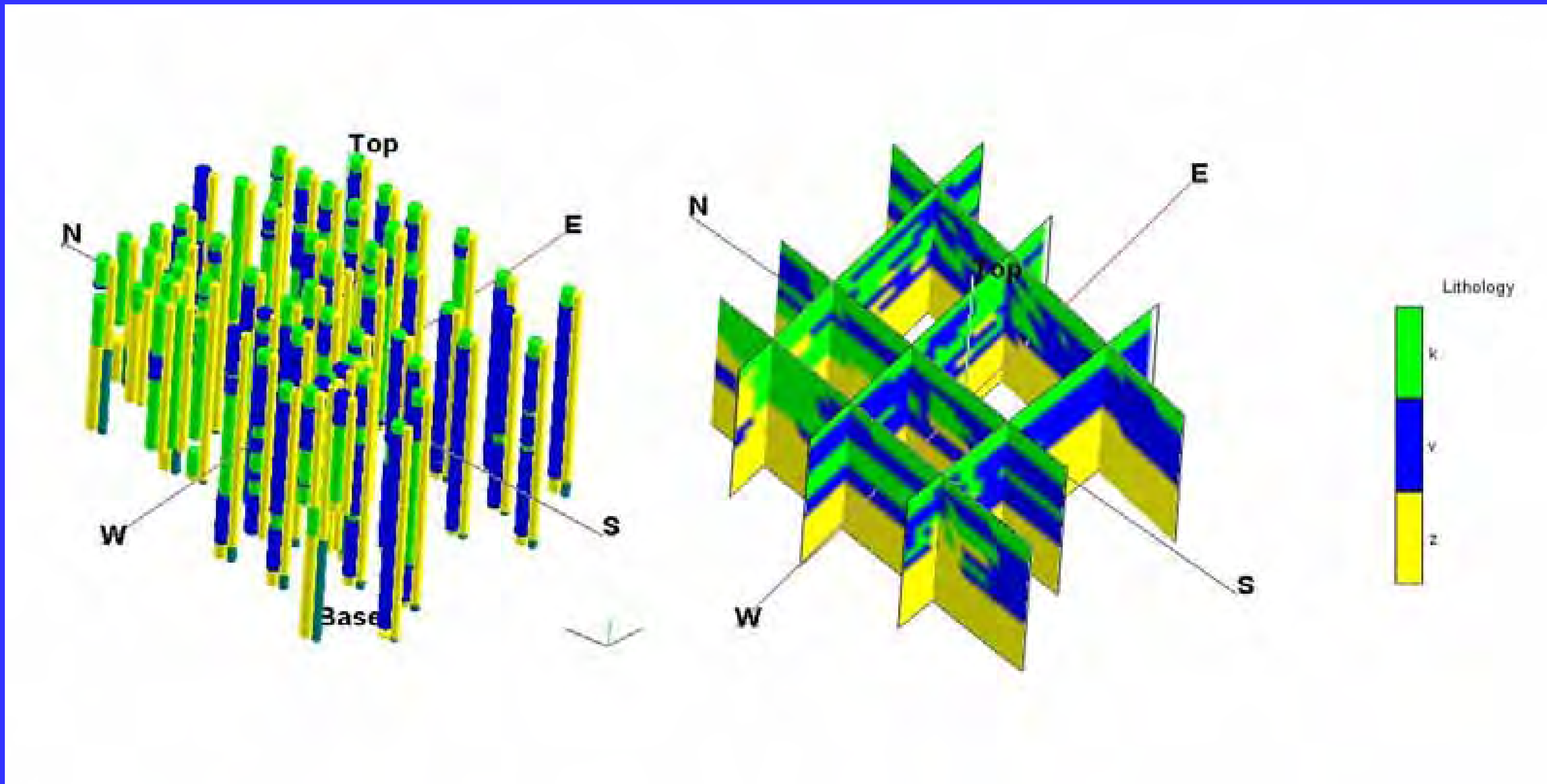


Case Study – Reeuwijk Road Project



A small area of 3.2 km^2 with 63 shallow boreholes

- A detailed lithological model can be built



Likelihood model

- Create a geological knowledge based system for reasoning of geological information
- Integrate knowledge-based interpretation into 3d modeling system
- Model likelihood index based on data quality, interpretation level, and model algorithm selection

Modeling Process

- Analyze the known data and information (geological, geotechnical, etc.)
- Build geological knowledge base system for reasoning of geological information used for interpretation
- Flowchart to interpret Pleistocene sand unit (Twente Formation)

Interpretation process

Types of knowledge used for Construction Geological Model (CGM):

$$CGM \in F(O, G, GU, ST, S, T)$$

O: Objective (Scale)

G: Geological Environment

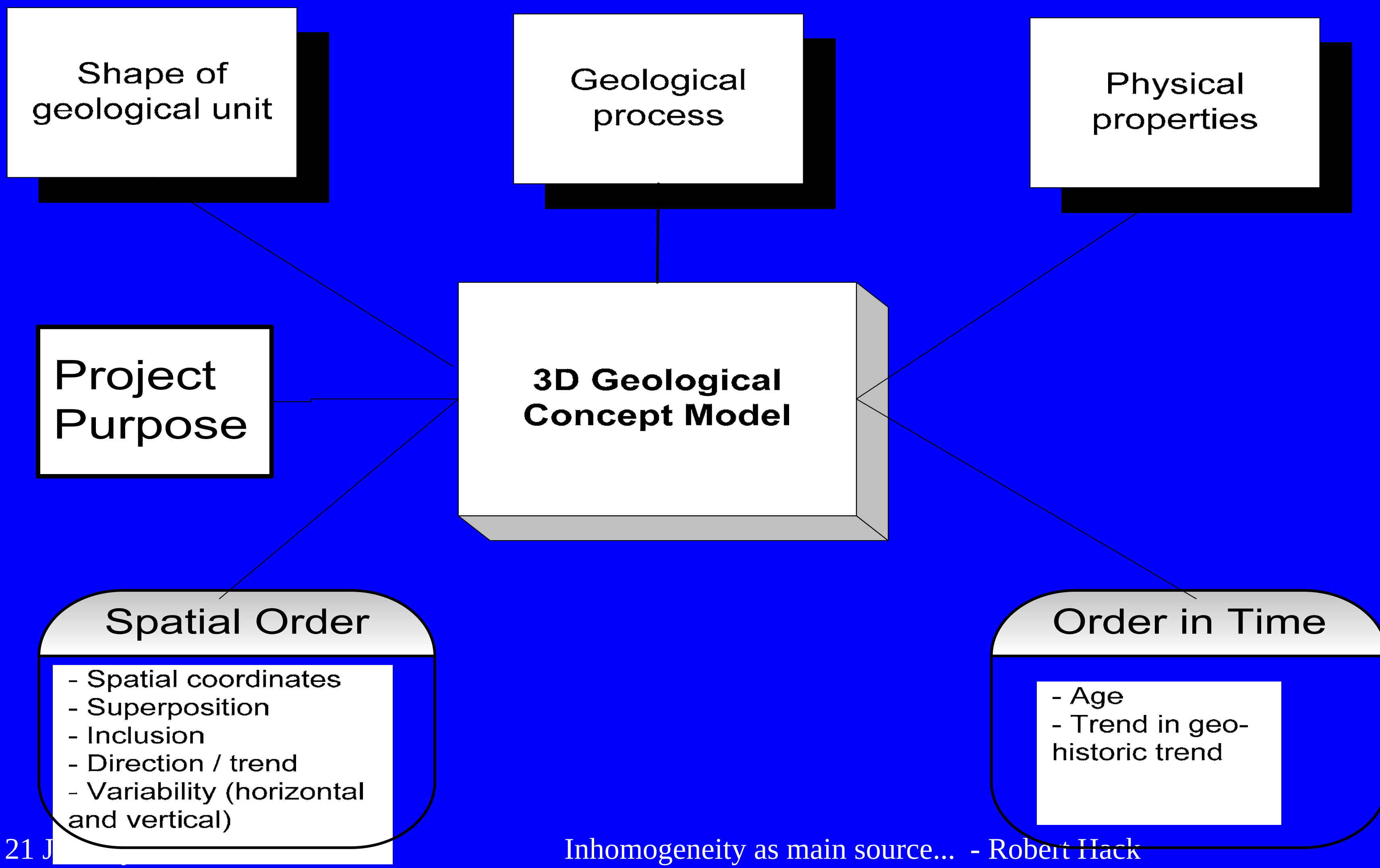
G: Geological units (types and numbers of that)

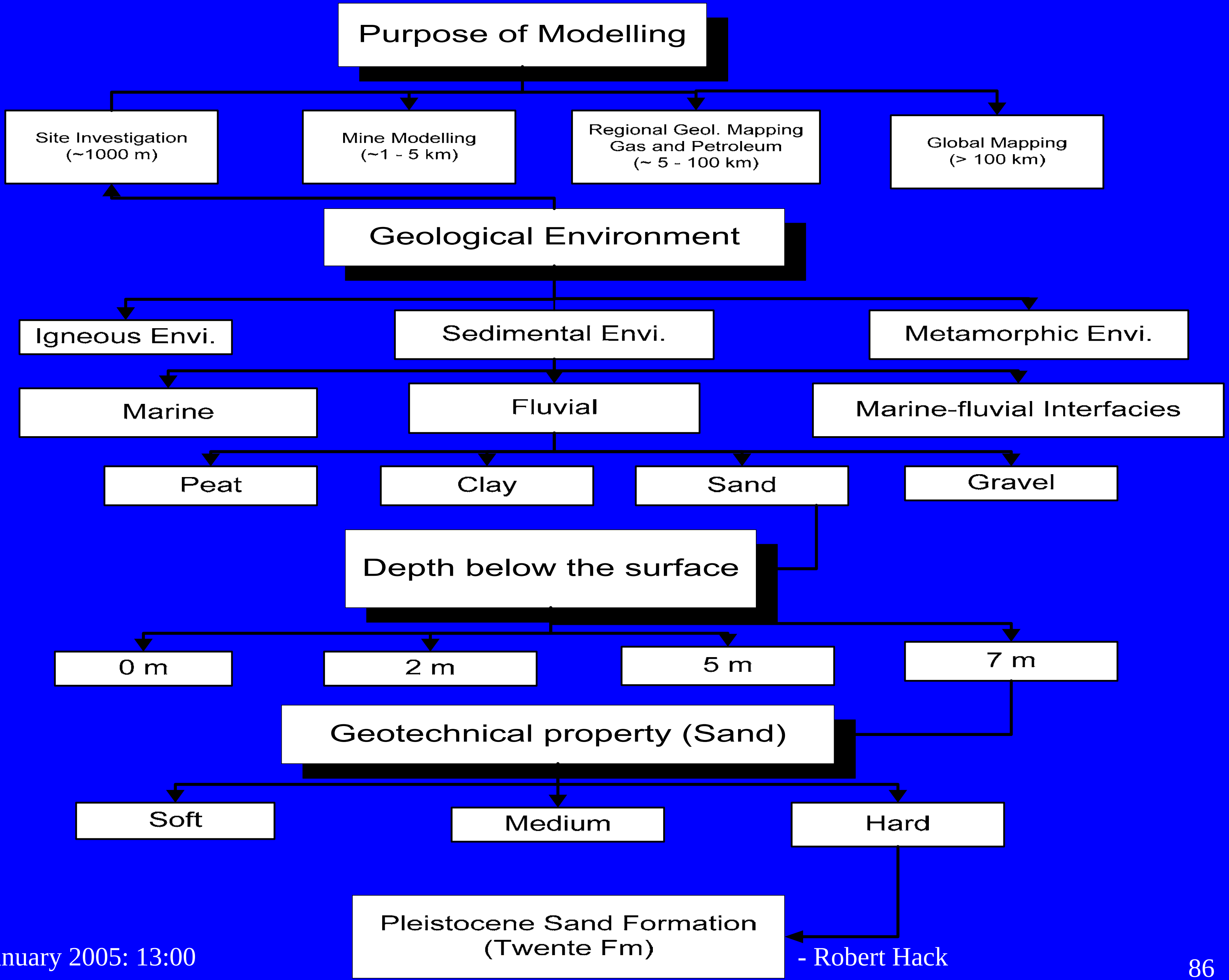
ST: Types of structures (fault, fold, fissure,…)

E: Spatial extent (X, Y, Z), spatial variation

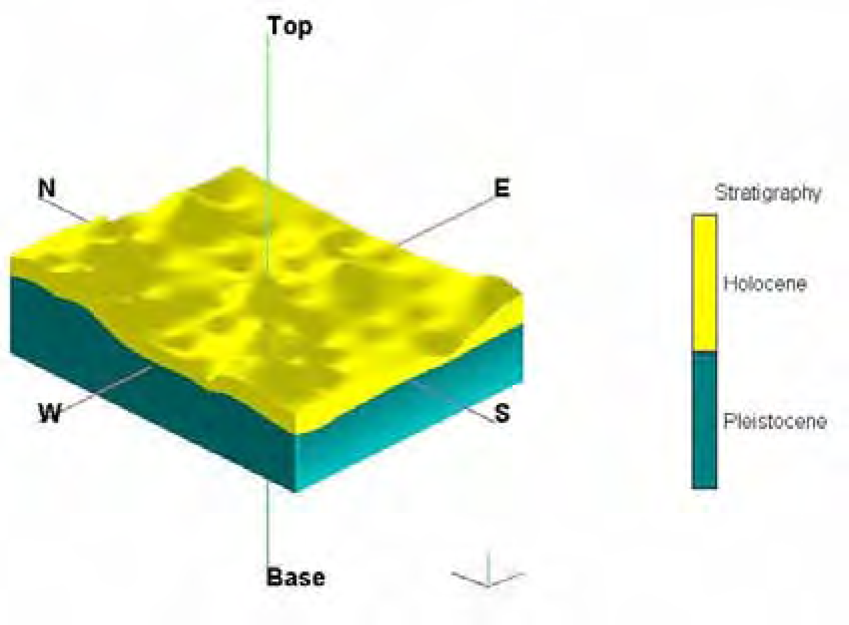
T: Time (age, geological evolution sequence of spatial features)

Interpretation for 3d modelling




Purpose of Modelling
Site Investigation (~1000 m)
Mine Modelling (~1 - 5 km)
Regional Geol. Mapping Gas and Petroleum (~ 5 - 100 km)
Global Mapping (> 100 km)
Geological Environment
Igneous Envi.
Sedimental Envi.
Metamorphic Envi.
Marine
Fluvial
Marine-fluvial Interfacies
Peat
Clay
Sand
Gravel
Depth below the surface
0 m
2 m
5 m
7 m
Geotechnical property (Sand)
Soft
Medium
Hard
Pleistocene Sand Formation (Twente Fm)

Model	Symbole	Unit /Formation	Description
1	Holocene	Westland Formation	Clay,sandy clay to clayey sand and peat
	Pleistocene	Twente Formation	Fine to medium sand
2	UHolocene	Tiel Deposits	Organic clay,sandy clay to clay sand and sand
	LHolocene	Holland peat,Gorkum Deposits,and Basal peat	Peat, mixture of clay, sandy clay to clayey sand locally with plant remains
	Pleistocene	Twente formation	Fine to medium sand (Cover sand)
3	UHolocene	Tiel Deposits	Organic clay,sandy clay to clay sand and sand
	MHolocene	Holland peat	Upper peat
	LHolocene	Basal peat and Gorkum Deposits	Lower peat and clay with remains of plant,sandy clay to clayey sand
	Pleistocene	Twente formation	Fine to medium sand (Cover sand)
4	Tiel Deposits		
	Holland peat		
	Gorkum Deposits		
	Basal peat		
	Twente/Eolian deposits		



- Model 1: two units

Holocene unit (top)

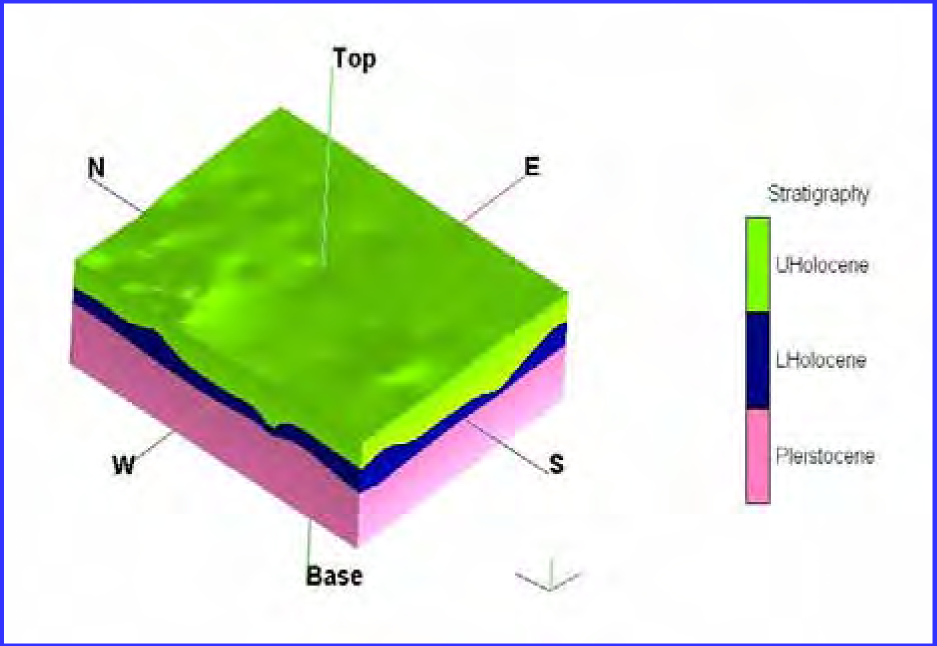
Twente Formation (sand) (bottom)

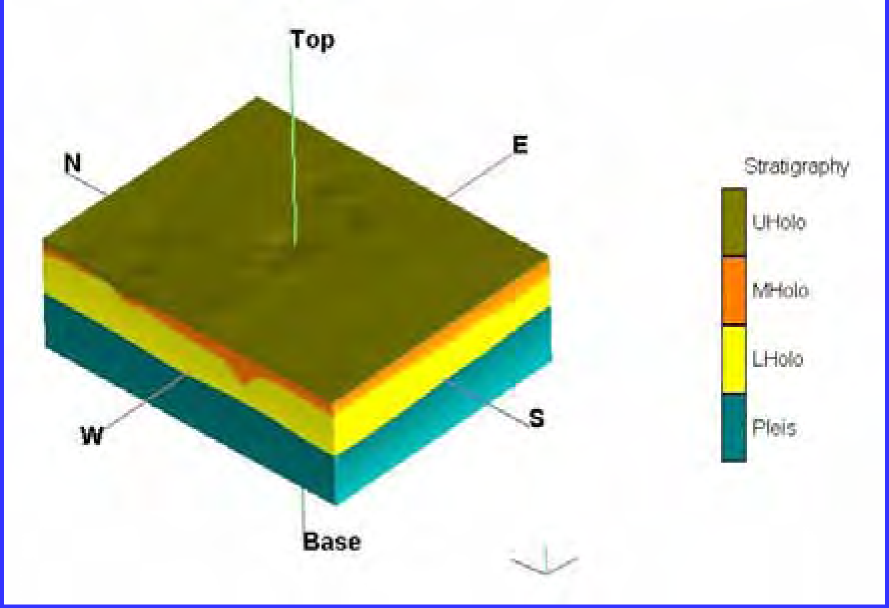
- Model 2: three units

Upper Holocene (top)

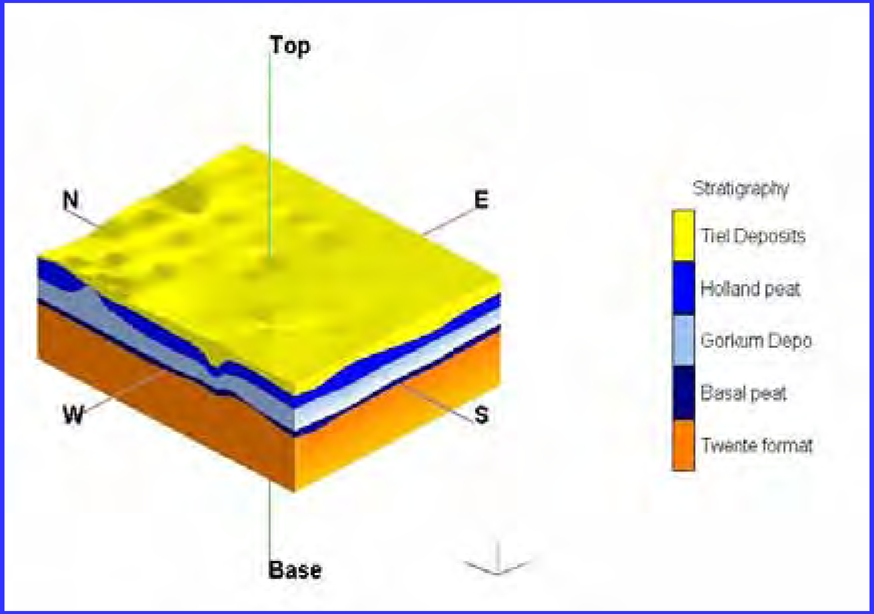
Lower Holocene (int)

Twente Formation (bottom)





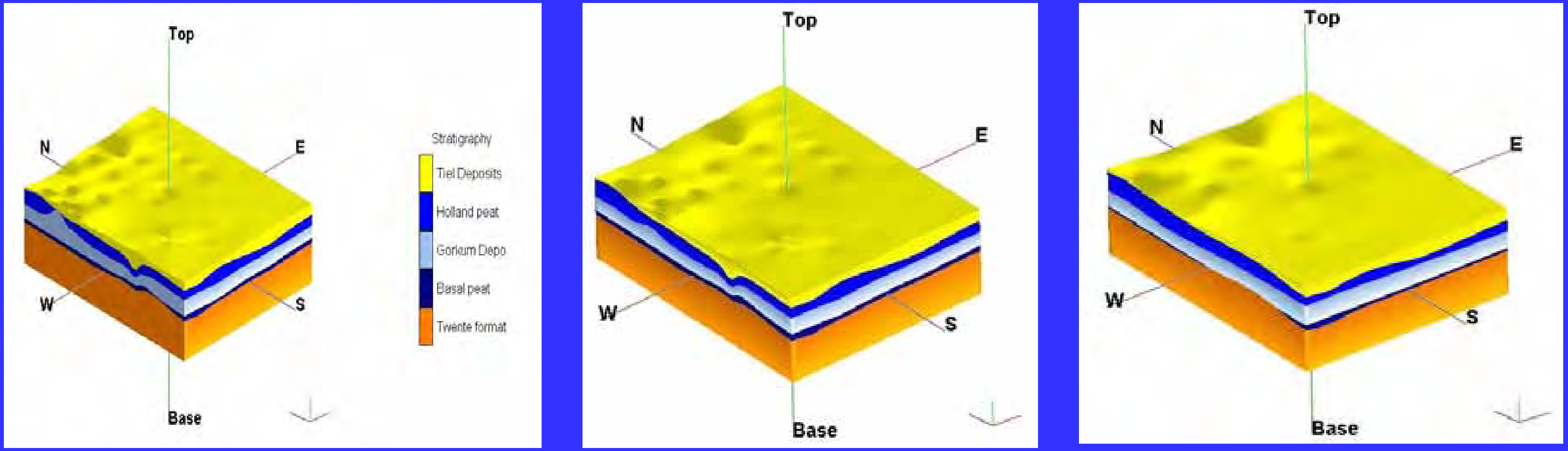
Model 3: four units

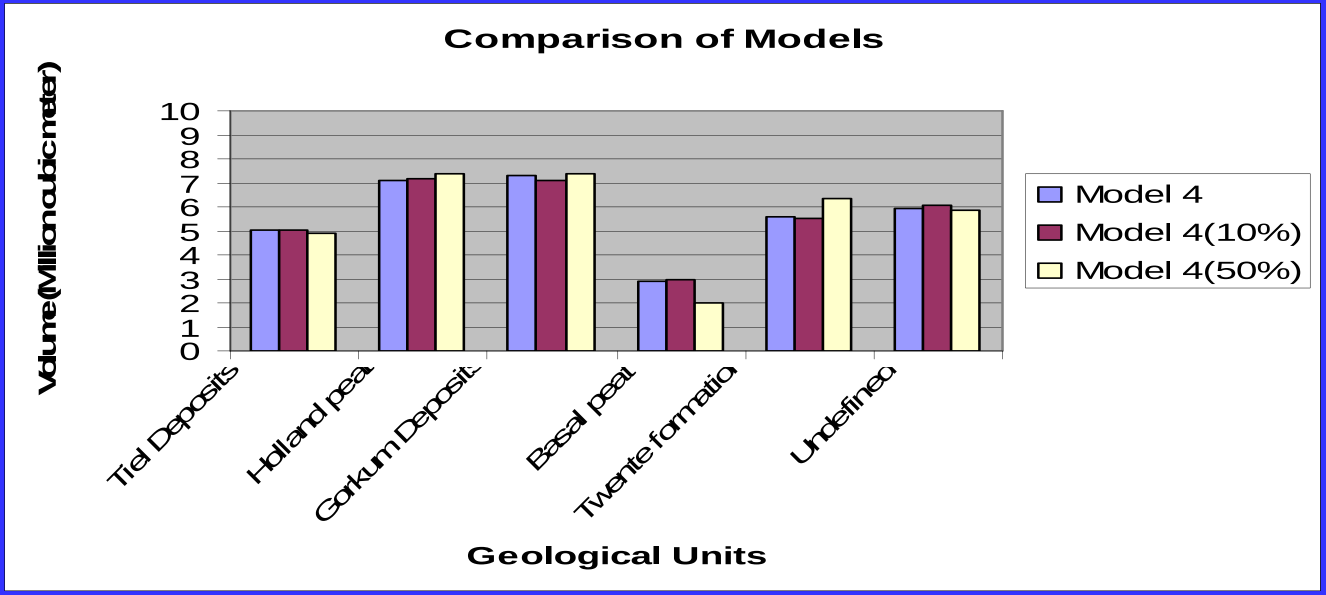


Model 4: five units

- Question: which model is more reliable for which purpose?
- Verification of models: decrease borehole data used

Model 4 (five units) worked out to be reliable enough





left: full data; middle: omitting 10%; right: 50% hole data

Conclusion Reeuwijk project:

- Models can be verified by decreasing input data
- Geological knowledge base can be created for reasoning general geological information for interpretation

Future degradation of soil or rock due to weathering, ravelling, etc.

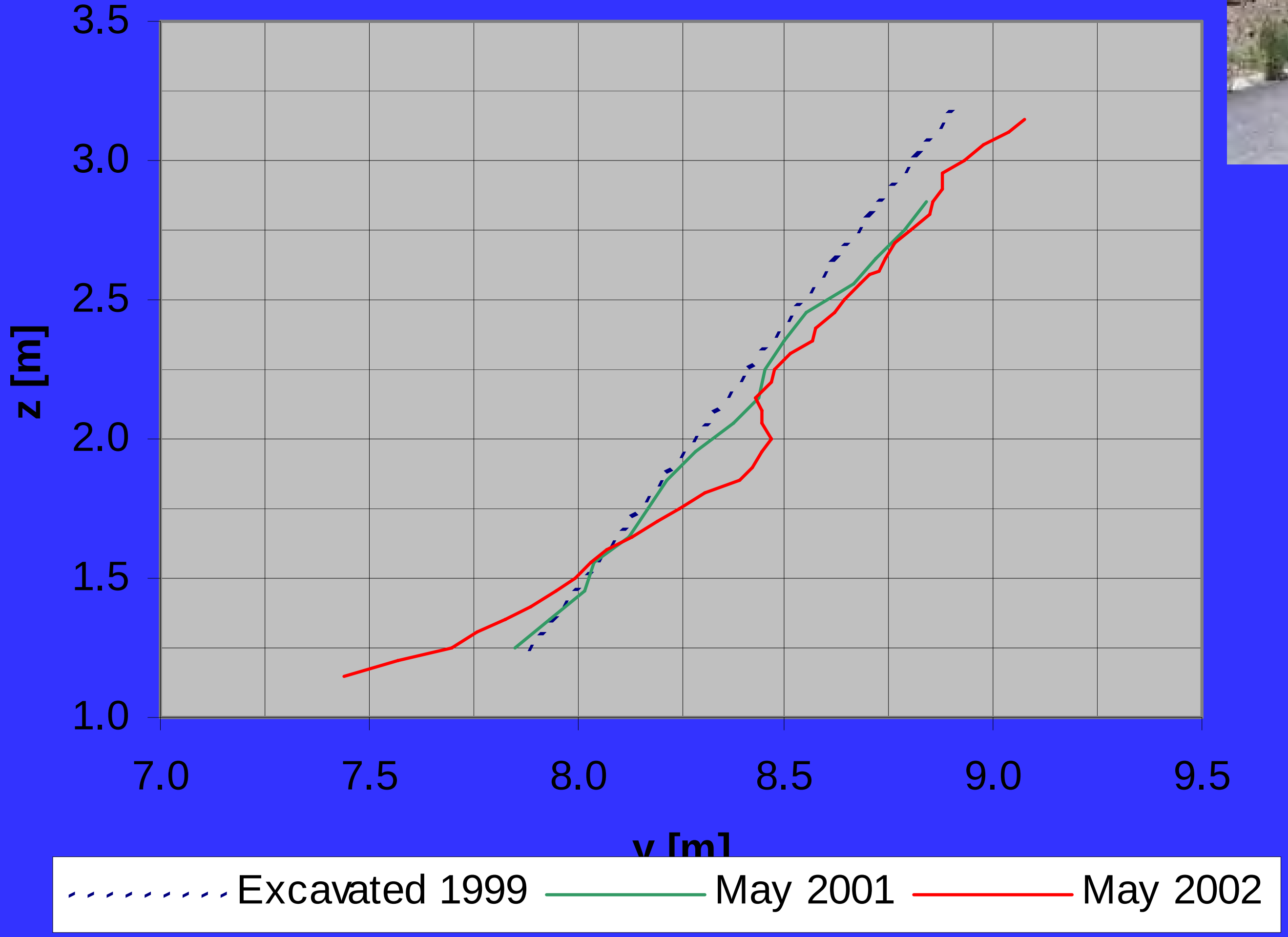
virtually no reliable quantitative relations exist to forecast the future geotechnical properties of soil or rock masses (within say 50 to 100 years)

however, it is known that a considerable variation exist in the time dependent degradation of rock or soil masses

Future degradation (2)

Gypsum containing siltstone (Keuper)

Future degradation (3)



Reduction in slope angle due to weathering, erosion and ravelling (after Huisman)

Conclusion

- Inhomogeneity is a problem
- Impact of inhomogeneity on design of civil engineering structures can be reduced by using more data or to do more with the data
- For both new options become available for engineering geology
- Time as factor in engineering geology needs considerably more attention