Special Course on Setting-Out Skyscrapers

Prof. Thomas Wunderlich
Dr.-Ing. Peter Wasmeier
TUM Chair of Geodesy

23.04.2018
Ballerup, DK

The course will be given by:

Thomas WUNDERLICH
Peter WASMEIER

Special Expertise:
Geometry
Tunneling
Monitoring
Refraction

Special Expertise:
Calibration
Metrology
Monitoring
Digital Image Processing

Some of our experiences with high structures

Santiago Calatrava
Coop Himmelb(l)au
Specific Features of Setting-out High Structures

- Project awarded most of all because of its design:
  - understand spirit (architect)
  - intended geometry (surveyor)
  - construction process (civil engineer)
  - system (formwork contractor)

- Establish faithful and regular communication with the above partners (coordinate system, special needs (e.g. plumbing shafts), working cycle, defined persons responsible)

- Take advantage of initial construction phase working out
  - to learn and improve your processes

- System (formwork contractor)

- Establish faithfull and regular communication with the above partners (coordinate system, special needs (e.g. plumbing shafts), working cycle, defined persons responsible)

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Tolerances and Standard Deviations

Tolerances are a value (given as an interval) which limit the allowable difference between a nominal and an actual measure.

Given a basic size maximum and minimum limits are given which mustn't be exceeded.

When objects change their value time- or load-dependent this is not subject to tolerances!

- Test tolerances immediately before changes appear
- Define a nominal influence setting for the measurement

Tolerances and Standard Deviations

The measurement process itself has an uncertainty which is part of the allowed tolerance:

$$ T = T_{\text{measurement}} + T_{\text{construction}} $$

Construction tolerance often is shared by different working steps, so there's usually a commitment which assigns different portions of the overall tolerance interval.

As nearly all measurements (99.7%) lie within a ± 3σ interval, $T_{\text{measurement}}$ usually gets defined as:

$$ T_{\text{measurement}} = 6\sigma $$

Slideshare.net (2018)
Tolerances and Standard Deviations

The relation between measurement uncertainty and tolerance is given as

$$V = \frac{T_M}{T}$$

with $V$ usually $\leq 0.2$.

Let the portion of tolerance $T$ available for the surveyor be $p$ [\%], then

$$T_M = \frac{1}{2} (1 - p)^{\frac{1}{2}}$$

<table>
<thead>
<tr>
<th>p [%]</th>
<th>T</th>
<th>$P_{\sim \alpha=0.05}$</th>
<th>$P_{\sim \alpha=0.01}$</th>
<th>$P_{\sim \alpha=0.005}$</th>
<th>$P_{\sim \alpha=0.001}$</th>
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</thead>
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<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Example:

The tolerance value is 20 mm. The surveyor is granted a 10\% share ($V=0.44$).

Then $T_M$ is 8.8 mm.

Depending on the necessary confidence interval the surveyor needs to choose a measurement strategy to fulfill that, e.g. for 95\% it's $\sigma = 2.2$ mm.

The surveyor can use a 11.2\% part of the overall tolerance as his aspired standard deviation.

Course Schedule

1. Static Concept
2. Plumbing
3. Upwards Transfer
4. Lateral Refraction
5. Coffee Break
6. Influences
7. Case Study
8. Lunch Break
9. Dynamic Concept
10. Plenary Discussion & Outlook

Setting-out on unsettled platforms

- The structure will be subject to deformations and motions of various type as well as of different magnitude and period.
- The influences increase with building height and become apparent from at least 100 meters on. They affect instruments, observations and surveying concepts.
- We must take into account:
  - Deformations:
    - subsidence (ground weakness, accumulative building load, changing ground water level)
    - effects of differential shrinking and creeping of concrete
    - thermal expansion
    - tilting
Setting-out on unsettled platforms

- We must take into account:
  - Motions:
    - bending (deflecting) due to insolation (daily period with seasonal variation) or static wind load
    - swinging (oscillating) due to wind gust excitation
    - vibration due to crane operation
- To cope with these contaminating side-conditions and to comply with the required tolerances we are obliged to follow one of two concepts, specially tailored for raising high-rise buildings.

### Static versus Dynamic Concept of Setting-out

**Static:** Transfer grid from ground floor to present top level at stable condition of structure; set-out from nominal position of top floor stations during unstable status

- Advantages: robust, low data load
- Disadvantages: cumbersome, expensive in time and workforce

**Dynamic:** Establish station on top level and determine instantaneous position with respect to special GNSS-targets; set-out from predicted instantaneous position

- Advantages: economic from time and workforce; reasonable investment needed
- Disadvantages: at the mercy of capable communication link; high data load

### Static Concept of Setting-out

We start with an introduction into the common construction approach and give an overview over the influences and problems making our surveying work particularly difficult.

### Common Construction Approach of Skyscrapers
Deformations due to Differential Compressions

The core runs ahead the platforms and experiences smaller compressions with increasing height than the pillars/columns bearing the platforms. In particular, when facade element installation and fitout starts before structural work is completed differential deformations impact facade element fitting (tensions) and elevator stops (step.s of 3 cm to 5 cm for 200 m height).

On the other hand civil engineers are anxious to close the structural shell early, because the gains in design firmness (structural analysis) only together with the facades completed.

Acting Forces

Periodic and independent Check Surveys to Confirm As-built Geometry – GNSS obstructed!

Plumbing
Instruments and Methods for Plumbing

- Mechanical plumbing (rather unsuitable for the particular construction and task)
- Optical plumbing
- Near vertical co-ordinate transfer

Precision Zenith Plummet & Special targets

Precision Plummet + Laser / Co-ordinate Transfer

Accuracies of plumbing instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freiberger precision zenith plummet FGL-100</td>
<td>$\sigma = 1 \text{ mm} / 100 \text{ m}$ (2&quot;)</td>
</tr>
<tr>
<td>Sokkia precision laser plummet LV1</td>
<td>$\sigma = 2.4 \text{ mm} / 100 \text{ m}$ (5&quot;)</td>
</tr>
<tr>
<td>FOIF Optical &amp; Laser Plummet DZJ2</td>
<td>$\sigma = 2.5 \text{ mm} / 100 \text{ m}$ (5&quot;)</td>
</tr>
<tr>
<td>FOIF Laser Plummet JC100</td>
<td>$\sigma = 1 \text{ mm} / 100 \text{ m}$ (2&quot;)</td>
</tr>
</tbody>
</table>

Old optical plummets deliver 1" at best
Example of plumbing system

Example of scaled plumbing concept

Example of scaled plumbing concept

Uncertainty propagation – direct/scaled plumbing

- Centering accuracy of the plummet
- Plumbing accuracy
- Centering accuracy of the laser dot

- 0.5 mm
- As given by the instrument
- 0.5 mm
- Laser dot size usually is 5 – 10 mm.

Now let’s compare results using a 2” plummet:

\[ \sigma = \sqrt{\sigma_C^2 + \sigma_L^2 + \sigma_P^2} \]

- Plumbing length should match the other non-length-dependent uncertainty factors and should be of equal influence
- Plumbing in two/four faces to increase accuracy!

Reference point at base floor

Make sure plumbing shafts stay clear

Example of scaled plumbing concept

Detection at upper floor

Example of scaled plumbing concept

Mechanical re-centering

Example of scaled plumbing concept

Next plumbing step

Clearance for plumbing

As a rule safety at work regulations will limit maximum clearance for plumbing openings with

\[20 \text{ cm} \times 20 \text{ cm}\]

resulting in problems, if – for an assumed centric position of the ground point – the deflection of the structure reaches or exceeds 10 cm.

In case the vertical line of sight for plumbing is prevented by such a deflection, there is still a method of coordinate transfer through the oblique shaft by a method successfully tried in France at the access shaft for the Channel Tunnel at Sangatte (J.J. Morlot, XYZ 1989; Wunderlich, 1997).

Applying the method takes some time, but renders respectable results and can moreover reduce the influence of lateral refraction effects or at least indicate refraction presence.
Co-ordinate Transfer ("Oblique Plumbing")

\[ z_1 = R \cos(B - x_0) + C \]

Function of Zenith Distance Readings \( z = z(\alpha) \)

Mathematical Model (Least Squares Adjustment)

Mathematical Model (Results, Accuracy)
Geometrical Model

Co-ordinate Transfer through Oblique Shafts

\[ T_2: \text{\( \frac{\Phi}{h} \) field of view} = \frac{29\,\text{m}}{1000\,\text{m}} \]
\[ \rightarrow \frac{\Phi}{h} < \frac{14.5\,\text{m}}{1000\,\text{m}} \]

Example: Shaft Tunnel Zell am See
\[ h = 480\,\text{m} \]
\[ \epsilon_{\text{max}} = 7\,\text{m} > 5\,\text{m} \]
\[ O.K. \]

For a building of 100 m height the shaft could be oblique up 1.4 m and we would still be able to complete a co-ordinate transfer by this method.

Upwards transfer of grids and networks

Establishing reference points for setting-out

After a start-up phase of several weeks a typical working progress could be one storey a week.

This results in different surveying processes:

- to bring up reference points (grid, network) to the next level(s)
- and to check compliance with the base grid/network on the ground level

This needs to obey:

- Different network hierarchies
- Transition steps in between
Network hierarchy

1 Site network (global reference)
2 Inner network (ground level reference)
3 Realized level network (temporary reference)
4 Working level network

- Surveying pillars in (and out) of working site
- Height reference points out of working site
- Suitable for both TPS and GNSS
- Repeated stability measurements
- Visual connection to working networks may be lost or reduced during working progress
- Dimension: distance from building at least height of building (due to GNSS)

2 Inner network (ground level reference)

- Persistently marked position and height control points
- Often only level accessible by levelling
- Part of global reference by connection to site network
- Starting level for plumbbines
- Repeated control measurements

3 Realized level network (temporary reference)

- All concrete work has been finished
- Persistently marked position and height control points
- Sometimes plumbing reference level
- Controlled in referencing epochs
- In between: acts as reference for all construction levels above
Network hierarchy

4 Working level network

- Formwork tables and supports present
- Concrete pouring still in progress
- Permanently changing situation
- Persistently or temporarily marked points
  Referenced from the last realized level network below
- Sometimes GNSS connected to site network (tall buildings)

Network transfer

Site network → Inner network

- Tacheometry, levelling
- Inner network often located on a single concrete foundation, therefore position relative to each other and building is highly stable
- But: underground movements, building pressure, basement construction (garages etc.) lead to absolute movements

Site network → Realized level network

- Tacheometry
- Depending on realized level height
- Slope views, influence of tilting axis error (two face measurements)
- Refraction effects only for longer distances (assuming 45° view, building height h, refraction coefficient error Δk = 0.5):
  h = 100 m, Δh = 0.4 mm
  h = 150 m, Δh = 1.2 mm
  h = 200 m, Δh = 2.2 mm

Inner network → Realized level network

- Plumblines (usually at least 3)
- Relay plumbing
- Vertical laser distance measurements or
- Hanging measuring tapes for height transfer
- Transfer to a discrete network
Network transfer

Realized level network → Working level network
Site network → Working level network

• Plumblines (usually at least 3)
• Relay plumbing
• Vertical laser distance measurements or
• Hanging measuring tapes for height transfer
• GNSS connection to site network possible (only tall buildings)
• Usually volatile due to working operation

Example of height transfer

Vertical laser distance measurements ending up in a levelling point

Network transfer using GNSS

• Individual reference station (using a fixed transformation parameter set)
• Commercial services:
  • HxGN SmartNet
    (Leica Hexagon, GPS-Reference)
    59 stations
  • GPSnet.dk
    (Geoteam, Trimble)
    25 stations

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### Network transfer repetition

<table>
<thead>
<tr>
<th>Level</th>
<th>Duration</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site network</td>
<td>1 – n months</td>
<td>Seasonal cycles</td>
</tr>
<tr>
<td>Ground level network</td>
<td>1 – n months</td>
<td>Depending on construction season</td>
</tr>
<tr>
<td>Lower realized level</td>
<td>1 – n weeks</td>
<td>At least together with ground level building variations</td>
</tr>
<tr>
<td>Top realized level</td>
<td>1 week</td>
<td>Proximity to working level</td>
</tr>
<tr>
<td>Working level</td>
<td>Daily / Permanent</td>
<td>Depending on construction</td>
</tr>
</tbody>
</table>

Often construction dependent measurement cycles get defined, e.g. to measure all levels every time a new one has been finished. This mostly also is part of the defined monitoring concept.

### Network transfer time slots and side conditions

Plumbing should be performed at times with little building displacements (no insolation, wind pressure, moving loads by cranes, vibrations etc.).

At the same time this means that the construction hoists (which according to regulations need an approved operator) will not be in service – all material hat to be carried up!

Three surveying parties have to simultaneously do the precision plumbing or co-ordinate transfer work.

There must be reliable communication devices for all.

As long as the structure is open (skeleton) no threatful lateral refraction effects will act; this changes dramatically when the construction becomes wrapped (glass facade installed) and concurrently numerous heating canons will be delivered and activated to dry out the concrete.

### Lateral Refraction – Physics and Geometry

\[
\kappa = \frac{1}{n} \nabla n^{-1}
\]

\(\kappa\)  ... Curvature of the projection curve in the plane S' 
\(n'\)  ... The unit vector orthonormal to the tangential unit vector grad \(n\)   ... Horizontal gradient of refractive index

The angle of refraction can be calculated via integration (Fearnley) to:

\[
\delta = \int_{\infty}^{\infty} \sin^{-1} \left( \frac{D - x}{x} \kappa(y) \right) dx
\]

\(\delta\)  ... Total refraction angle at observation station
Lateral Refraction – Physics and Geometry

For the numerical integration over the light ray curvature (assumed to be constant for the given area) the following applies:

\[ \delta = \sum \frac{D - x}{B \cdot s_i \cdot \Delta s} \]

D... Total length of the target ray from station point to target [m]
s... Distance from the station point to the middle of the interference zone [m]
\( \Delta s \)... Length of the interference area [m]
\( \delta \)... Angle of refraction [cc = 0.1 mgon]

Horizontal Refraction from Atmospheric Data

The light ray is thereby broken down into n partial segments \( \Delta s \), such that the aforementioned assumption remains valid.

\[ \kappa = -2.2 \cdot \frac{P}{T} \cdot \frac{\Delta s}{D} \]

P... Mean air pressure [mmHg]
T... Mean air temperature [K]
\( \kappa \)... Constant curvature of the light ray [cc/m]

The highly dominating influence comes from the temperature gradient \( \Delta T \)!

In tunneling for scientific investigation of the lateral refraction effects (in particular at the portal) a very accurate determination of the horizontal temperature gradient has to be managed.

There, inside the tunnel the gradient is caused by time independent different temperature of rock and tunnel ventilation; at the portal a daily variation is superimposed by sun radiation.
In Plumbing Lateral Refraction must be kept away

Influences on buildings and measurements

List of Influence Sources
1. Building weight and material
2. Foundation force changes
3. Ground water pressure
4. Dynamical & changing loads
5. Building material changes
6. Wind pressure
7. Temperature changes
subsidences, settlements, tilting
subsidences, settlements, tilting vertical deformations, tilting
deformations, tilting, vibrations
stress, strain, deformations vibrations deformations
Periods of influence sources

<table>
<thead>
<tr>
<th>Source</th>
<th>0.1 sec</th>
<th>1 sec</th>
<th>10 min</th>
<th>1 h</th>
<th>1 day</th>
<th>1 month</th>
<th>1 year</th>
<th>10 years</th>
</tr>
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<tbody>
<tr>
<td>Subsidence</td>
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<tr>
<td>Vibrations</td>
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</tr>
</tbody>
</table>

Building reactions

- Rigid body movements (similarity transformation)
- Inner deformations (local affine transformation)

Building reactions

- Bending line movements at high buildings
  - Use a chain of measurement points
  - Calculate the maximum deviation when using a linear simplification

And overall:
Is it irreversible, plastic or elastic?
Results:
- Lower storeys become stressed
- Upper storeys become constructed too high

Building load during construction process

Concrete shrinking

Foundation force effects
- Very slow foundation changes depending on
- Increasing building weight
- Ground water changes
- Long-term effects
- Different soil stability
- Mainly shows subsidences / settlements, but may also lead to tiltings.

Foundation deformation measurements
- Repeatedly check building AND building area
- Repeatedly model the actual situation and predict future behaviour
- Set Measurement points at
  - the „weakest“ points
  - the most threatened points
  - the points showing most effects
- Settlements, subsidences
  - immediate
  - Consolidation
  - secondary

Concrete shrinking

Bachmann (2013)

Additional load by ith storey
- ~30 – 50 mm at up to 200 m
- 600 mm at Burj Khalifa, tower, 828 m

VDZ Zementtaschenbuch (2002)

Foundation force effects

Concrete shrinking
Wind load effects

• Vibrations especially at tall buildings like towers: Karman's turbulences leading to lateral oscillations biggest at cylindrical towers, less at big prismatic buildings

  usually \( 0.15 < f < 1.5 \) Hz

• Bending is usually only a minor effect as residence time is too short

Wind load effects

Example: TV tower Stuttgart
6 cm x 8 cm movement in 20 sec

Wind load effects

Horizontal movements by wind effects

Example: Munich Olympic tower:
100 consecutive epochs of 20 second inclination periods with ellipsis fitting

→ Changing ratio between along track
   and across track amplitudes

→ Short time stability only

Extreme example: Burj Khalifa tower

Height: 570 m, movement 125 cm
Height: 375 m, movement 50 cm
When the building is vibrating or swinging, automatic compensators mostly need to be turned off!

(Hz Correction may still be on)

And: automatic levels may stop working due to their swinging compensator!

→ use analogue tube levels instead
→ wait for a proper measurement slot

Measurements at windload

When turning the compensator off:

• Measurements no longer are related to the vertical line, but to the instrument’s setup axis.
• Setting up the instrument is difficult:
  • Watch the bubble level (or electronic compensator values) and level to a mean value
  → tachometer axis is vertical best possibly
  • Operate with tilted setup axis and use reference points and a spatial transformation
  → tilting can be calculated or compensated and use two-face measurements

Assume we have 10 mm swinging at 100 m height: 6.4 mgon tilting

For a 25 m stakeout point this would lead to a maximum of

• 2.5 mm vertical displacement at horizontal view
• 1.1 mm horizontal and 2.3 mm vertical displacement at steep view of z = 70 gons

Temperature effects – Munich Olympic Tower

• Inclinometer „Nivel“ measurements

<table>
<thead>
<tr>
<th>Temperature effects – Munich Olympic Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>• GPS / TPS monitoring on some sunny summer days</td>
</tr>
</tbody>
</table>

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Never plumb at sunshine!

Temperature effects – Munich Olympic Tower

• GPS / TPS monitoring on some sunny summer days

Temperature effects – Munich Olympic Tower

• Three different methods of vibration measurements with different frequency spectrum

Example: Munich cathedral

Temperature effects – material expansion

Typical horizontal deformations due to thermal expansion per year (up to 6 mm)
Temperature effects – material expansion

Special displacements due to extremal temperatures

Outside temperature from 0 °C → -12 °C → 10 °C
4 mm displacement!

Mean thermal expansion coefficient of ferroconcrete: $12 \cdot 10^{-6} \mu m/m \cdot \Delta T$

Due to material and construction method this value may change by 30%.

This may especially lead to shrinking/expanding of high buildings:

$1.2 \text{ mm} / 100 \text{ m} \cdot \Delta T$

Problems:
• During construction building centers (core shafts) and peripherals get produced at different times -> always obey relative heights and measures
• During usage e.g. elevator steps may be displaced

Temperature effects – concrete buildings

Hotel „Maritim“ in Travemünde – 110 m

Temperature effects – SAR example

S. Gernhardt / R. Bamler (2012)
Shrinking and creeping effects

- Changes during construction process
- Yearly period changes
- Unreversible, long-term changes

Dynamical & changing load effects

- Snow and ice masses (especially on roof structures)
- Moving construction elements (cranes, climbing scaffolds)
- Moving elements during use (bells, panorama restaurants)

Dynamical & changing load effects

- Example: inclinometer measurements due to crane movements at ECB Building
ECB Towers „New Premises“

- Entrance building
- Office twin towers
- Old market hall
- Loading yard

ECB Towers „New Premises“

- 120,000 m² land area
- 185 m high (north tower) / 165 m (south tower)
- 110,000 m² of floors
- Construction time: 2010 – 11/2014
- Costs: 1.3 billion €
Challenges for surveyor

- Towers change contours from a rectangle to a trapezium (north tower) resp. opposite direction (south tower) and are tilted by 9°
- Due to the contour changes not only settlements and stresses appear, but also tiltings and rotations
- To achieve nominal construction, this behaviour had been simulated and added to the construction plan
  -> Surveyours needed to monitor the lower floors permanently to check whether the simulated displacements would appear or have been over/undercompensated
- 3 cones per tower would take elevators later, so vertical accuracy is crucial here after displacement consolidation
- Construction time: 6 days per storey

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ECB Newsletter 7 (2013)
Self-climbing platform

Tilted cores

Steel girder links between towers

Windshields are obstacles for surveying
**Demand accuracies**

**Rule of thumb:** Surveying accuracy is about 20% of overall dimensional tolerance.

At ECB building surveying accuracies were...

- Cones: ± 8 mm
- Other 2D accuracies: ± 6 mm
- Height accuracies: ± 5 mm

**Predicted deformation compensation**

Each storey gets transformed individually before staking the points out.

**Logistics and human resources**

- **Planned:** project leader and 2 surveying teams
- **Necessary:** 2 project coordinators and 6 surveying teams
- **Surveying timeslots only rarely timed — very often „surveying on demand”**

**Definition of surveying concept**

- Definition of site network (3D surveying pillars) — constr. site
- Definition of inner network (2D reference points and levelling points) — Level 0
- Both towers are located on the same baseplate
- Definition of plumbing reference points — Level 0

Coordinate system layout:
- Parallel to construction axis definition
**Definition of surveying concept**

Instruments to be used:

- ZNL for optical plumbing / instrument centering (1 mm / 30 m)
- GeoLaser L2000 (5 mm / 100 m)
- Motorized tacheometer Trimble S6 (0.15 mgon, 2 mm + 2 ppm)
- Leica NA 3003 level

Measurement frequency:

- While levels 1 – 15: after each level all reference points of subjacent levels
- While levels 16 – 25: after each second level all reference points in any second level
- While levels 26 – 45: after each second level all reference points in any fourth level

Measurement frequency is to be adopted during construction process.

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**Definition of surveying concept**

- 2D accuracies stated in the proposal:
  - Fixed point accuracy due to monitored network adjustment: 2 mm
- Plumbing:
  - Fixed point accuracy due to monitored network adjustment: 2 mm
- Plumbing height (segments) | Standard deviation (σ) mm
  - 0 – 50 m (1) | 3.8
  - 50 – 100 m (2) | 4.1
  - 100 – 150 m (3) | 4.6
  - 150 – 200 m (4) | 5.5

Plumbing to each level starts in level 0, but is done in max. 50 m segments

- Centering: 0.5 mm
- Free Stationing at a given level: 2 mm
- Polat point measurement: 2 mm

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**Definition of surveying concept**

- Height accuracies stated in the proposal:
  - Fixed point accuracy due to monitored leveling adjustment: 0.5 mm
  - Levelling and trigonometric height transfer: 1.4 mm
  - Height transfer via laser through plumbholes: 1 mm

- Accuracy monitoring:
  - Site network is re-monitored after level 5 and level 10
  - Coordinates and height are re-transferred to inner network to monitor displacements of the whole building baseplate
  - Deformation monitoring in upper levels according monitoring plan of 4 – 8 marked points per level to check the predicted building movements

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**Special part: Steel girder links**

High accuracy demands in an as-built situation:

Special network between both towers to survey the tags

Thomas Wunderlich | Peter Wasmeier | Setting Out Skyscrapers Course | Ballerup, April 23rd, 2018
Surveying concept: plumbing

Totally 14 plumblines have been established (4 in south tower, 6 in north tower, 4 in the atrium).

Plumbing holes are of 20 cm x 20 cm size and need to be secured throughout all working steps.

... but plumbing proved to be problematic:

- Working time from 4 a.m. to 7 a.m.
- Obstacles in the plumbing lines
- Holes need to be held open and filled much later
- Interior work already begins during construction

For upper levels (above 100 m) there was a need for a supplement of plumbing lines!

Surveying concept: plumbing

Investment: GNSS and inclinometer sensors

5 GNSS sensors (1 reference and 4 rovers)
Dataloggers and software
4 inclination sensors
~ €120 000 total net

Investment: GNSS and inclinometer layout
Investment: precise inclinometer sensors

6 inclination sensors
Communication equipment
~ 43 000 € total net

Investment: precise inclinometer layout

GNSS usability study

Question: Individual on-site reference station or virtual network reference station?

Result:
on-site: 94 % ambiguity fixing, difference to plumbing results < 1 cm
network: 76 % ambiguity fixing, difference to plumbing results ~ 2 cm

Question: How long need the GNSS points to be observed to converge to mm accuracy?

Result: usually ~ 45 min due to different and changing occlusions
Remark: height accuracy = 15 mm

Results: Comparison of GNSS and inclinometer
Result: Inclinometer measurements

- No significant movements up to 100 m of building height
- Amplitudes (mostly random) of up to 3 cm during construction time
- Very little movements from 3 to 7 a.m.

Result: deformations smaller than predicted

- Only little influences by wind loads
- Significant influence by sun (~4 cm in July)
- Expected deformations 15 cm in floor 25 were far to big compared to real deformations
- Always use optical plummets which allow two-face (four-face) measurements (not only tripod included optics)

Measurement experiences
Modern dynamic measurement concepts for setting out skyscrapers

Why a dynamic concept?

Buildings becoming taller and taller...

Traditional geodetic approaches will no longer be sufficient.
For every high-rise building setting out has to be done with respect to main vertical reference lines (usually inside the core elements).

Close to the ground it is no problem as there are surrounding reference points. But a few hundred meters high…

- … no sightlines to ground control points
- … building is bending and swinging due to loads, wind etc.
- … building is lifted due to settlements, concret shrinking, construction tolerances

How to work in the design coordinate system, regardless of building movements?
Plumbing is no longer an alternative and reference points have to be changed rather quickly.

Why a dynamic concept?

We don’t want this…

but rather that…

Who has invented it?
The principle was first introduced by Leica Geosystems in the beginning of the 2000’s.
The head was Joel van Cranenbroeck, which nowadays runs his own company „Creative Geosensing” in Belgium.

Most of the work presented in this chapter is directly related to him, as it is currently state-of-the-art.

Components

- GNSS Sensors
- Tachometers
- Inclinometers
- Meteorology sensors (temperature, pressure, humidity, wind speed and direction)
- Radio and/or network links
- Calculation server
- Visualization components
- Online connection to transfer processed data on-site
For example: Leica Nivel 210, DigiPas DWL 5800XY
Precision and resolution <= 1"
Measuring time < 1 Hz
Very important:
- Index error and temperature calibration
- Long-term stability

Trend:
+0.4 μrad / year

For example: Leica GM30, Trimble Alloy
Using monitoring or chokering antennas
Measurement frequencies up to 50 Hz
(with suitable software)
but only 1 Hz necessary

Stable reference station (also monitored) necessary!

For example: Leica TM30, Trimble S8
Motorized, radio connected
Calibrated regularly
Proper 360° prisms

With or without inclination sensor
and at least 3 of them

Combination of Sensors for an „Active Point“

Tacheometers

Combination of Sensors for an „Active Point“

GNSS sensors
Local transformation parameter set to express GNSS measurements in the local site system (7 parameters)

- Especially to rotate the ellipsoidal WGS84 z-direction to a local geoidal height direction (most crucial component)

Usually one calculates the transformation parameters from long-term observation campaigns of ground network control points.

- Consecutively re-checked and tested for consistency with the inclinometer data and the active point coordinates by e.g. precise levelling at higher construction levels

ACP coordinates are transformed from WGS84 to local site system and to TPS system using a reference station located on construction site.

Inclination chain to detect a non-linear bending

- or

Single inclination sensors on top to approximate linear behavior

Important:

- Orientated along the building axes

Continuous data allow to separate persistent long-term effects like settlements from reversible high frequency effects like windload
Dynamic concept 1 – TPS and inclinometer

Dynamic concept 2 – TPS and GNSS

Measurement principles

Post processing mode
- Active Control Points measured
- Other surveying is performed
- GNSS data stored on controller is evaluated and transformed to site system
- Transformation from TPS system to site system is calculated
- Surveying data is transformed to site system
- Return to site to survey again

Real-time mode
- Active Control Points measured
- GNSS data is streamed to a laptop on site and transformed to site system
- Transformation from TPS system to site system is calculated
- Other surveying is performed
- Surveying data is transformed to site system on TPS or on a connected laptop
- Active Control Points measured in between

Measurement principles

GNSS filtering methods against outliers / mean values during TPS measurement epoch
Measurement principles

- TPS observations on Control Prisms work on a Least Squares Adjustment evaluation
- Sensor time series will control each other (e.g. GNSS and inclinometers)
- Workflow:
  - TPS is set up first wherever it is needed.
  - Active Control Points then may be set up wherever they find a suitable place for the current TPS setup. ACPs may also be permanently set up on surrounding buildings.
  - Check compensator usage (perform 2-face-measurements)
  - Measure the ACPs
  - Measure the rest...
- TPS observations could be corrected not by a mean value but by a time series – but usually differences are rather small.

Dynamic concept for monitoring

[Diagram of dynamic concept for monitoring]

Market alternatives

Trimble High-Rise

- Interface to Trimble 4D Control Monitoring solution

Trimble High Rise App at Lakhta Center

[Images of Trimble High Rise App at Lakhta Center]
Vertical or not vertical only has one answer: Surveying!

Discussion …