# Evaluation and Prediction of High-rise Building Settlements based on Satellite Data

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High-rise buildings in the western part of The Netherlands are subject to settlement as a result of compression of deep-lying cohesive layers. The size of the compression and creep deformation depends on the load increment in the compressible layers which is determined by building dimensions, permanent load and foundation level. In addition, the properties of the compressible layers are important. A great uncertainty herein is the pre-consolidation stress or initial creep rate of these layers. On the basis of InSAR – satellite data of existing high-rise buildings, the current settlement rate can be measured and a good estimate is possible of, in particular, the pre-consolidation stress in the compressible layers resulting in the observed settlement rate.

## Preface

Buildings with a height over 100 meters are increasingly being realized. Such high-rise buildings are usually founded on piles with a pile tip level in a deep sand layer. In the western part of The Netherlands, these are usually the Pleistocene deposits at a depth of order NAP -25 m (Dutch datum level is approximately sea level). Below the foundation level, compressible layers may be present. These layers give rise to settlement of the high-rise as a result of permanent load. With regard to high-rise buildings in Rotterdam, Hannink, G. (1994) provided a good overview for ten buildings. Hannink draws the conclusion that the load increment in the deep layers can be determined sufficiently accurate, but that there is lack of monitoring data.
In the context of a Bachelors thesis for the Rotterdam University of Applied Sciences, it was investigated whether satellite data can be used to determine the settlement rate of high-rise buildings and provide the missing link with settlement models.

## Satellite Data - InSAR

Since 1992 there have been satellites in the sky which, using a technique called InSAR , make images of the Earth. These images can be used for different purposes. Monitoring settlement of buildings is one of them.

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Processing the raw satellite data into usable and editable data is a specific and time-consuming task. If there is sufficient data available, the vertical displacement of objects can be determined as shown in Figure 1.


**Figure 1:** Data for a point at the World Port Center in Rotterdam.

InSAR is short for Interferometric Synthetic Aperture Radar. From a satellite radar waves are transmitted to earth. The reflection is then collected by the same satellite. The collected radar waves provide an amplitude and a phase. The amplitude of the reflection gives a 2D image. The phase of the reflection gives a phase image. By comparing two phase images with each other, an interferogram can be made. These steps are shown visually in Figures 2, 3 and 4.

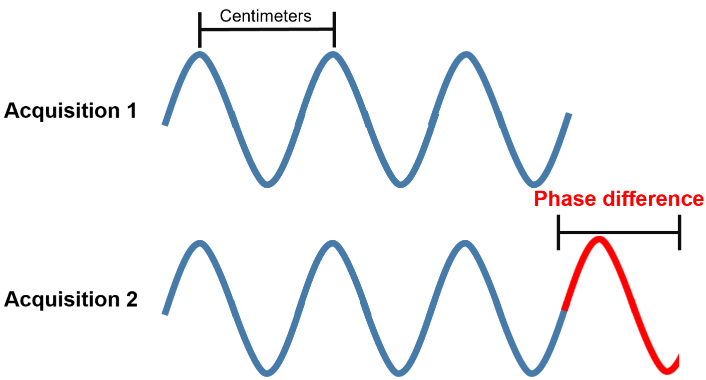


**Figure 2:** Radar wave interpretation.

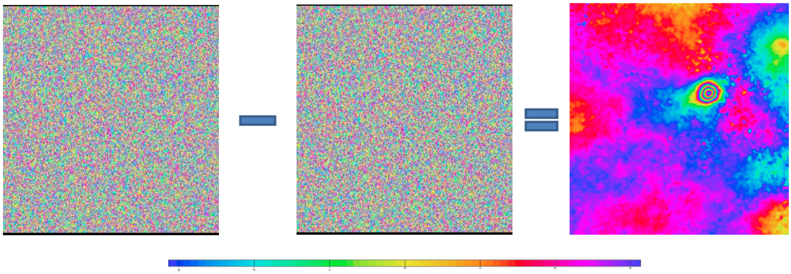

**Figure 3:** Interferogram derived from the comparison of two phase images.

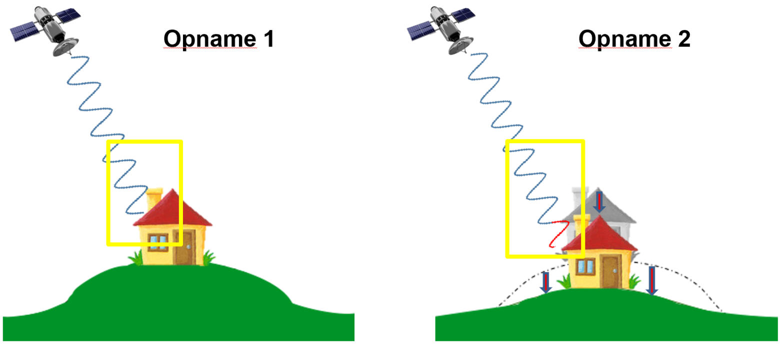


**Figure 4:** Interpretation displacement.

By comparing interferograms, recurring points can be found, so-called coherent scatterers . Since the phase difference is known, the vertical displacement of each point can be calculated. The angle at which the satellite radar signal transmits is known, from which the vertical displacement are calculated with the Pythagorean theorem . With this method an accuracy of 1 to 2 millimeters, can be achieved . The exact height determination does not follow from the interferograms and differs per method. High-resolution data provide an accuracy of 1 to 1.5 m in vertical direction, and in the horizontal plane in the order of

1 to 2 m (SKYGEO).
Every passage of a satellite produces an interferogram . It is important that objects are present in the same state at every passage. If this is not the case, the object will be filtered from the data. Examples are a parked car not placed at the same spot every passage, a tree whose branches and leaves move in the wind, but also a building that is being erected in scaffolding. Figure 5 shows how the radiation reflects at different objects.

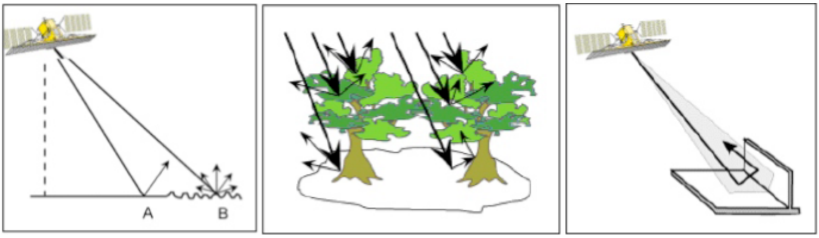


**Figure 5:** Reflection on different objects.

A satellite has a specific orbit around the earth. Due to the movement of the satellite relative to the rotation of the earth, a certain point can be viewed from two different angles. A distinction is made between an ascending and descending path. In an ascending the satellite moves from the equator toward the North Pole; in the descending path the satellite moves from the North Pole to the equator.
By comparing ascending and descending satellite data, the east-west movement of a point can be observed. The phase change of the signal is translated into a vertical displacement. When a point experiences a small horizontal movement towards the east, the satellite in a descending orbit will observe a shortening of the phase; in the ascending orbit the satellite will observe an extension of the phase. In the processing of the data, this extension and shortening is then translated into a vertical displacement: a displacement upwards for the shortening of the phase and a displacement downwards for the extension of the phase.
Many buildings show a settlement trend which on average has a downward trend. This trend indicates a settlement of the building. In addition to the trend, another phenomenon is visible in the measurements. Figure 6 shows the settlement trend on a building, measured with the TerraSAR -X satellite in the descending orbit.
In addition to the linear trend of -0.7 mm per year, a sine wave variation is observed. Looking at the peak moments of the sinusoid, it can be seen that they are in the warmer period of the year, and the low values apply to the colder period of the year (summer/winter). This effect can be attributed to thermal expansion of materials.
The opposite effect is visible in Figure 7. This figure shows the vertical displacement of a low elevated point, measured by the same satellite in the descending orbit. In this case the point is 1.05 meters below the reference plane; the location applies to a road. The peak values of the sinusoid appear in the cold season and the low values in the warm period of the year. A theory that explains this behavior is the influence of the groundwater level

which is higher in winter than in summer.

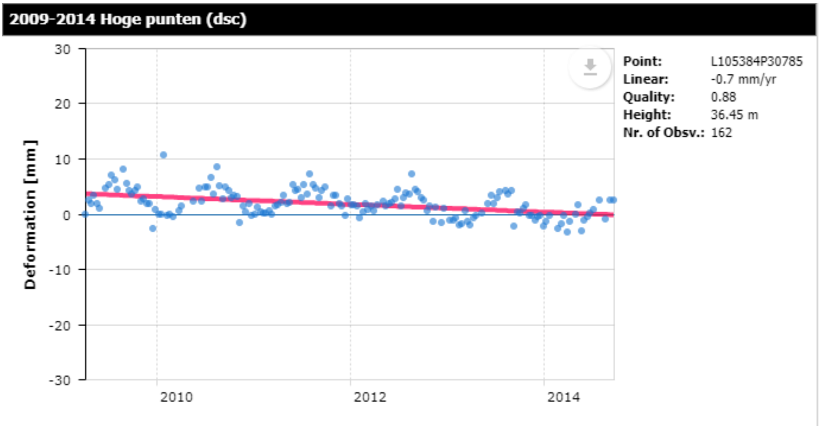


**Figure 6:** Vertical displacement according to InSAR of a point on a building.

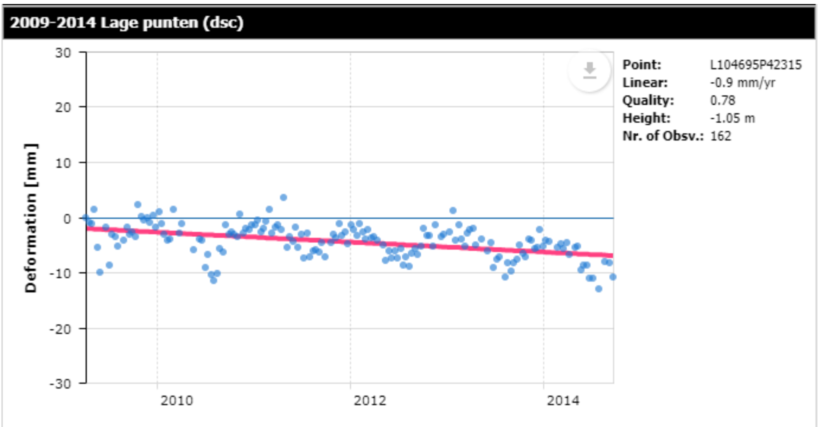


**Figure 7:** Vertical displacement according to InSAR of a low point.

## Description Settlement Model

Analyses of the compression of deep cohesive layers starts with the determination of the load increment in these layers. The permanent load acts at pile tip level or slightly higher, across the area of the pile foundation. By taking into account the load distribution, the stress increment in the compressible layer can be determined. Next, a settlement model and a consolidation model are selected. Preference is given to an isotache compression model such as the NEN-Bjerrum isotache - or the A, B, C- isotache model . Both models perform better with a small load increment, provided that a realistic initial strain rate is used. The compression parameters can be determined from a 7-stage oedometer test or a CRS (Constant Rate of Strain) test. The pre-consolidation stress, OCR or initial strain rate can be calibrated to satellite observations, increasing the reliability of the prediction. In addition, a consolidation model is required to describe the dissipation of excess pore pressure resulting from the load increment.

## Case study

A case study was conducted on the settlement behavior of three buildings in Rotterdam in The Netherlands (Figure 8), World Port Center, Montevideo and New Orleans. General data of the buildings are given in Table 1.


**Figure 8:** High-rise Buildings Rotterdam.

**Table 1:** General data.

| Building | Completion [-] | Height [m] | Length [m] | Width [m] | Pile Tip Level [m + NAP] | Load [1] [kPa] |
|---|---|---|---|---|---|---|
| World Port Center | 2001 | 123 | 50 | 34 | -22 | 336 |
| Montevideo | 19-12-2005 | 152 | 30 | 26 | -22 | 645 |
| New Orleans | 16-11-2010 | 158 | 30 | 30 | -22 | 660 |

[1] Total building load on pile foundation.

SkyGeo provided satellite data (TerraSAR -X high resolution) for the buildings in Rotterdam regarding the period April 2009 to September 2014. The World Port Center and Montevideo were completed prior to the measuring period. Although the New Orleans building was not yet completed in 2009, there are sufficient points available to derive the settlement rate. The InSAR satellite data are given in Figure 9 to 11.

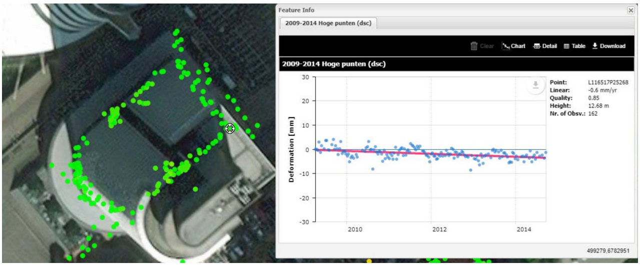


**Figure 9:** World Port Center settlement trend high-rise.

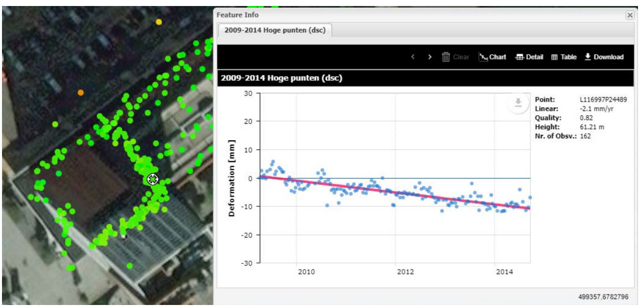


**Figure 10:** Montevideo settlement trend high-rise.

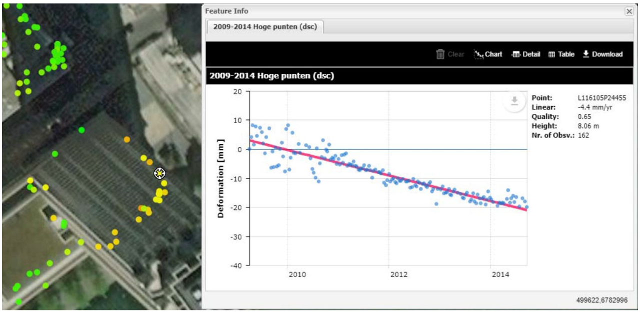


**Figure 11:** New Orleans settlement trend high-rise.

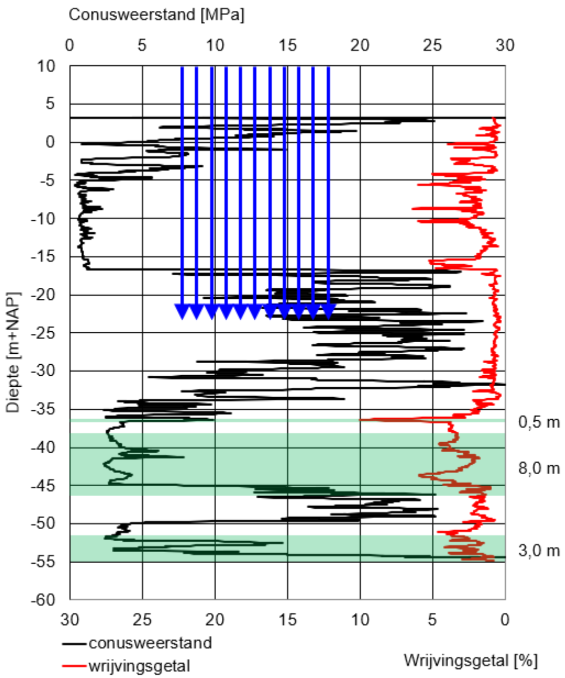


**Figure 12:** Characteristic soil stratigraphy Rotterdam.

The measuring points are located on the parimeter on the buildings, which are distorted by the 3D presentation of the view. The measurements presented relate to characteristic points, without a statistical analysis conducted and show a clear difference in settlement

rate ranging from 0.6 mm/year for the World Port Center, 2.1 mm/year for Montevideo and 4.4 mm/year for New Orleans.
For the soil conditions at the location of the three towers, the data from a nearby building "De Rotterdam" was used. Fugro conducted a soils investigation to large depth, including bore hole sampling and laboratory tests on the deep clay samples . A characteristic Cone Penetration Test is shown in Figure 12.
Below the Pleistocene foundation layer, starting at NAP -17 m, there are three clay layers up to a depth of NAP -55 m with a total thickness of 11.5 m. The clay layers are shown schematically in green as well as the thickness of the layers.
The compression parameters, applicable to all Pleistocene clay layers at this location, are derived from the IL oedometer tests conducted for the "De Rotterdam" project (Fugro archive). The NEN- Bjerrum isotache model has been selected with:

- CR, Compression Ratio = 0.100
- RR, Recompression Ratio, RR = CR/8 = 0.0125
- $C_\alpha$ Secondary Compression Coefficient, $C_\alpha$ = CR/20 = 0.0050
- OCR, Over Consolidation Ratio = 2.0

In the isotache model, the OCR determines the initial strain rate $\dot{\varepsilon}$, so without a load increment, according to the equation:

$$\dot{\varepsilon} = \frac{C_\alpha}{\ln 10} \cdot OCR^{\frac{-(CR-RR)}{C_\alpha}}$$

Applying these parameters results in an initial strain rate equal to $1.2 \cdot 10^{-8}$/day. With a layer thickness of the compressible Pleistocene layers of 11.5 m, this corresponds to a background settlement of 0.050 mm/year. The settlement calculations are conducted with commercial software D-Settlement (DELTARES), with the load data according to Table 1 (uniformly distributed at pile tip level), effective start of loading 24 months before completion, soil stratigraphy according to Figure 12, settlement parameters as given above, and a consolidation model according to Terzaghi with a consolidation coefficient of $4 \cdot 10^{-7}$ $m^2$/s. The results apply to a vertical through the center of the buildings. In addition, the settlement parameters are fitted to the satellite data. This has led to the same NEN Bjerrum set of parameters for all three buildings with an increment of the OCR from 2.0 to 2.25.
With this modified OCR, the initial strain rate equals $1.5 \cdot 10^{-9}$/day, corresponding to a substantially smaller background settlement rate of 0.006 mm/year.
In Figure 13 to 15 graphs are given of building settlement according to InSAR-data, the original parameter set (Ref) and the calibrated parameter set (Fit). It is concluded that the settlement calculation based on the calibrated parameter set, which is the same for all three buildings, corresponds well with the measurement data.

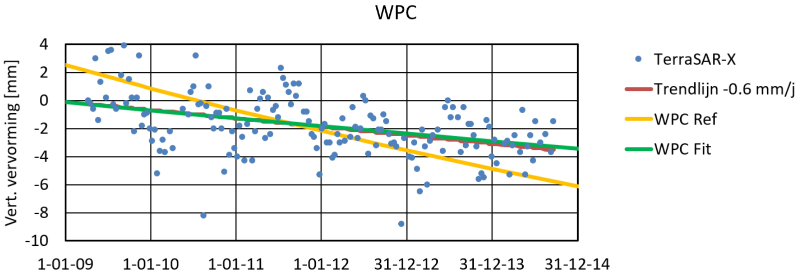


**Figure 13:** Calibrated and original parameter set with respect to InSAR data, WPC.

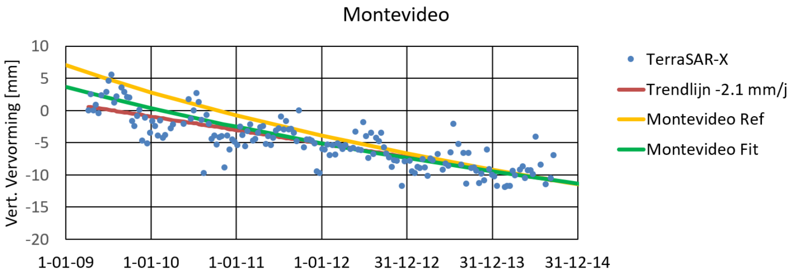


**Figure 14:** Calibrated and original parameter set with respect to InSAR data, Montevideo.

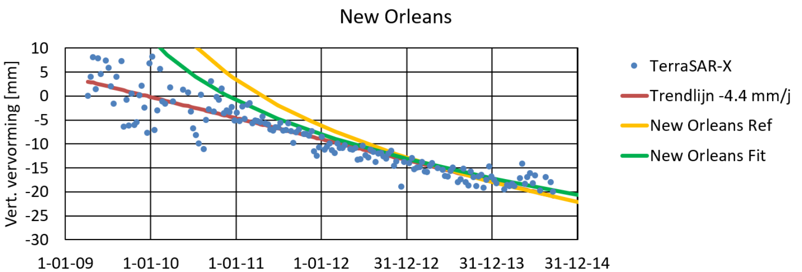


**Figure 15:** Calibrated and original parameter set with respect to InSAR data, New Orleans.

In addition, in Figure 16 to 18 the calculated settlement is given for the three buildings from start loading up to present with the original parameter set, the calibrated parameter set and the satellite data. It is noted that an offset has been added to the satellite data in order to match the building settlement at the moment the measurement series starts.

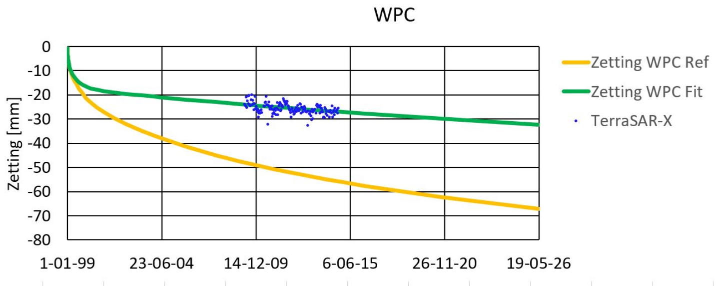


**Figure 16:** Settlement trend calibrated versus original parameter set, WPC.

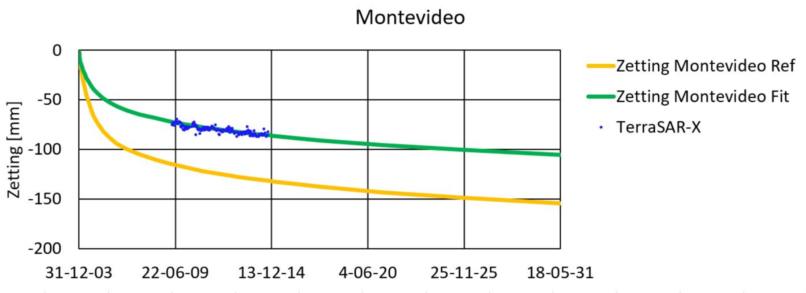


**Figure 17:** Settlement trend calibrated against original parameter set, Montevideo.

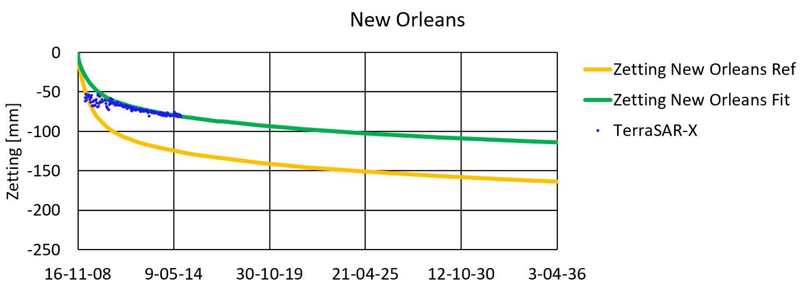


**Figure 18:** Settlement trend calibrated versus original parameter set, New Orleans.

## Conclusion

The prediction of the settlement behavior of high-rise buildings is subject to uncertainty. This applies in particular to the initial creep strain rate (background settlement) of the compressible layers below pile tip level. This creep strain rate is largely determined by the OCR, which can be determined from IL compression tests with relatively low reliability. This is partly due to the fact that the OCR in the isotache model does not only describe the historic in-situ vertical effective stress, but is also determined by the age of the deposits and the past time of creep.

The TerraSAR -X satellite provides high-quality InSAR data from which the settlement rate of high-rise buildings over the relevant measurement period can be deduced.

In the NEN Bjerrum isotache model, the over consolidation rate (OCR) is calibrated with satellite data, in such a way that the settlement rate during the measurement period corresponds to the calculated rate in the same period. Analyses of three different buildings in Rotterdam has led to one unique parameter set despite relatively large differences in load and completion date which results in a large range of momentary settlement rates (from 0.6 to 4.4 mm/year).

Based on calibration of the NEN Bjerrum isotache model to satellite data from nearby high-rise buildings, the reliability of settlement analyses has improved considerably.

## Acknowledgement

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