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UTILISATION OF A 3D DESIGN DATA IN CONTROLLING PILE DRIVING

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ABSTRACT

This research was concentrating on an exploitation of 3D design data to ground strengthening, especially focusing on the pile driving process. An XML model (schema) was defined for digital piling plan and as-build-data from the piling. The schema was targeted to cover the complete piling information flow from the piling plan from the 3D CAD software to the actual pile realization data e.g. location and bearing capacity data, produced by the piling machine. In addition to the information management, a guiding system for the piling machine driver was developed. The guiding system included sensors and RTK-GPS positioning system for measuring the location of tool of the piling machine in relation to the planned locations of the piles. The system gives visual instructions for the driver for positioning of the piles according to the plan. A wireless database connection is used for synchronization of the planned and realized piles information. The progress of the piling work can be easily supervised using an internet browser. The first proof-of-concept system was developed and tested during the year 2009. The main advantages of the system are reduced staking out work, faster pile positioning, automated piling data logging and data transfer between office and worksite and more up-to-date information about the progress of the piling work.

Keywords: pile driving, product modelling, positioning, RTK-GPS

1. INTRODUCTION

The research presented in this paper is part of the POHVA2 research project. In POHVA2 project the goal is to apply ICT, 3D modeling, machine automation and wireless data communication in ground strengthening. The research work is focused on two different ground strengthening methods, pile driving and deep stabilization. Pile driving is a commonly used ground strengthening method in both building and infrastructure construction. In pile driving an special machine, a piling rig, equipped with an hydraulic hammer, is used in installing steel reinforced concrete piles. Deep stabilization is a method used in soft ground. In deep stabilization columns are made mixing binding agents to the soft ground (e.g. cement and lime) using a deep stabilization machine. The common feature of these two ground strengthening methods is that CAD software is used in design of the piles and columns. Design data consist of the 3D locations of the piles or columns and also other properties, e.g. desired bearing capacity. In the worksite piles or columns should be positioned according to the CAD data. This paper is focused on pile driving and utilization of 3D data in controlling pile driving.

GPS based positioning systems are extensively used and researched in construction (Roberts et. al 1999). An RTK (Real Time Kinematic) GPS provides real time position data within accuracy of few centimeters, which makes it very useful in construction applications (Peyret et. al 2000, Saghravani et al. 2009). RTK GPS is commonly used in machine guidance and machine control applications and especially machine guidance systems in excavators are common. Automated system for piling rig positioning has also been developed (Seward et. al. 1997), but in piling most of the research work is focused on determination of the bearing capacity of the piling and usually automation is not applied to positioning. Methods for automating, collecting data of the piling events and providing guidance for the driver are studied for auger piling process (Mure et. al. 2002).

The prototype system developed in this project is for machine guidance. It gives instructions for the operator during the work and also handles data collecting tasks and thus eliminates the need for paper documents. The goal of the study is the automated and extendable piling data flow between all the actors in the process, work machine, design software and a data storage. For fluent data exchange between different systems and applications data formats were developed using an XML (eXtensible Markup Language).

Machine guidance is based on GPS positioning. Two RTK GPS receivers are used for positioning the frame of the machine and determination of the direction of the machine (figure 4). This method is used also in machine guidance systems of the excavators (Makkonen et. al. 2006). One aim of the project is to reduce the positioning time of the pile. According to the measurement most of the time spend in piling is the actual piling work, but also handling of the piles including positioning can be 25 – 40 % of the total working time depending for example the length of the piles (Paitsola 2008). Actual time spend in positioning is about 5 - 10% of the total working time, but the biggest advance of the guidance system is that staking out of the positions of the piles is not needed in the worksite. The problem with the staking out is that sometimes piling work has to be stopped in order to wait the survey personnel to perform staking out. Also when the piling machine is moved, wooden stakes are easily run over.

In Figure 1 a simplified piling workflow with corresponding functions of the automated guiding system are presented. The piling work is divided into a subtasks and a guiding system provides information during each subtask. Positioning of the pile is done first positioning the bottom of the pile. Then the pile is straighten or tilted to a desired position. Usually piles are installed straight, but in some cases tilted piles are used also. During the hammering it is important to keep the mast of the piling machine aligned with the pile, because decentralized hammering can cause breaking of the pile. After the piling work the realization data from the piling process is stored to a database.

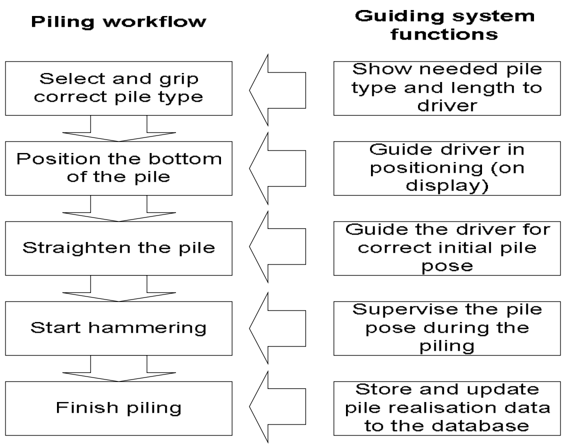

Figure 1. The piling workflow and corresponding guiding system actions.

The main target of the study was to speed up the piling process and improve the documentation and the information transfer between the actors of the process. The completely new idea in this study was the fluent two-way information flow between the design software and the guidance system of the piling rig. Wireless data transfer is used for connecting piling machine to the database. Current mobile phone networks and wireless data transfer networks offer broadband connections to the work machines. In the case of piling the progress of the work can be monitored using a web based tools in real time. This is useful for logistics and project management.

2. UTILISATION OF A 3D DESIGN DATA IN PILING

2.1. Xml based data format for a digital piling plan

One of the most important goals of this study was to integrate the information exchange mechanism between the design software and the work machine. Piling is done both building and infrastructure construction, so compatibility with CAD software used in both areas is needed. Our approach was to select technology that is commonly used. Our goal was an open format for digital piling plan that can be easily extended to other applications and work machines, e.g. deep stabilization machines.

The XML language was selected as basis of the development work. In other application fields there is also need for data exchange formats between machines and other systems, etc. CAD software or project management software. IREDES (International Rock Excavation Data Exchange Standard) is used in mining industry. In Finland and other Nordic countries forest industry in an important field of industry and StanFord-XML (Standard for Forest Data and Communications) is developed for forestry machines.

In construction industry there is currently no open exchange standard for different construction machines, but the LandXML format is common data exchange format between CAD and other software (e.g. surveying software) used in infrastructure sector. Some features of the LandXML specification are also usable in machine guidance and control applications. LandXML format includes for example 3D surface models that can utilized by 3D machine guidance systems (LandXML). Extensions to LandXML format were developed in Finland in Inframodel2 project (Inframodel2). The LandXML and Inframodel2 specifications include definitions that are well documented and useful in piling application also (e.g. <Units>, <CoordinateSystem> and <Application> elements). For that reason LandXML and Inframodel2 definitions were taken as a basis for data exchange format in piling. In this project XML elements and properties for piling data were defined (e.g. <PilingPlan> and <PlannedPile> elements) and XML schema was defined for exporting piling plan from CAD software. An example of the piling plan XML data can be seen in figure 2.

```
<PilingPlan>
    <PlannedPile Id="512" status="planned" size="300x300" pileClass="PL2" pileType="driven enbearing"
    pileMat="concrete" pileToeType="rockshoe"
    designedLoadCapacity="800" x1="6696654.744000" y1="2542994.358100" z1="12.000000"
    x2="6696644.744000" y2="2542993.358100" z2="20.000000"/>
</PilingPlan>
```

Figure 2. Example of the elements of the XML based piling plan.

2.2. 3D design of the piling

Generation of the XML piling plan has been made easy for the design engineer. Piling can be designed using a 3D design software (Figure 3). A software plug-in is added to a design software, Tekla Structures in this case, that automatically generates a piling plan in the defined XML format. The piling plan includes all the desired information of the planned pile, e.g. the top and the bottom coordinates, bearing capacities, materials, etc.

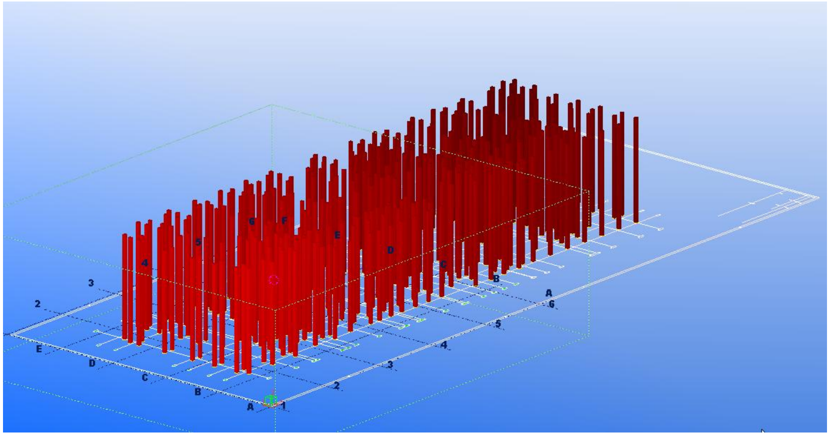

Figure 3. 3D Design of the piling using Tekla Structures software.

2.3. Positioning of the piles according to the digital piling plan

The generated digital piling plan can be transferred to the piling rig as an XML file either using a portable mass memory like USB memory or using a wireless connections to the database. If a database connection is used, an XML file is generated from the data retrieved from the MySQL database. The XML file is then read into the piling guidance software. During this phase the XML file is validated using the XML schema. Data content of the XML file is defined in XML schema and the XML schema can be is retrieved either from the internal memory of PC computer or from the web server. During the piling process the realization data is logged to the particular XML realization file. The XML retrieving procedure also works similar way from the rig to the database, so as-build-data is stored to a database and is available for example to the designer or contractor via internet. The piling data is then parsed from the XML file and shown to the user by the guiding software. The operator of the machine can now choose the correct pile and the guiding software provides guidance through the different phases of the setting the position and the orientation of the pile. According to the literature the positioning accuracy should be about ± 2 cm (Paitsola 2008).

3. PROTOTYPE SYSTEM

3.1. Overwiew

Designed prototype system was built on a Junttan PM-20 pile driving rig (figure 4). The systems consists of an in-vehicle PC with Windows operating system and touch screen, two Trimble RTK GPS receivers and sensors for measuring the positions of the actuators of the machine and orientation of the frame. Wireless internet connection was implemented using Flash-OFDM mobile broadband network. Remote MySQL database and local XML files were used as data repositories. The overview of the system is presented in figure 5.

Figure 4. Junttan PM-20 piling rig.

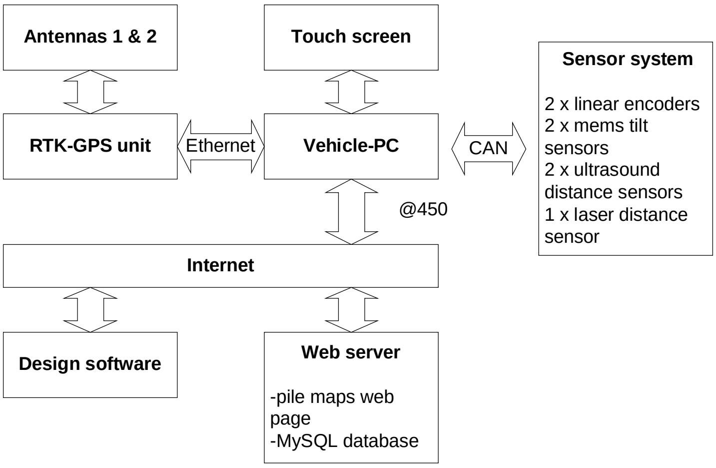

Figure 5. Overview of the prototype system.

At the beginning of the project the researchers observed piling work at the worksite (Paitsola 2008). This was useful when the requirements for the new prototypes system were defined. Most important requirement was easy to use guidance system for positioning the pile. The piling guidance system should also support some special cases, e.g. inclined piles, extended piles and extra piles that are added by the machine operator. One requirement was a general method for data exchange with CAD programs. An XML based extendable and generic format for the digital piling maps was seen as an important feature. Wireless broadband connection offers many possibilities in machine control applications and one goal was to utilize wireless communications in transferring piling data. One benefit is that if there are more than one piling rig working in the same site, the progress of the work can be synchronized between piling rigs. Also the progress of the work can be supervised using the web based supervisor view.

3.2. RTK GPS units

The positioning system used in this prototype system was Trimble SPS-850 RTK GPS receiver that provides around 1 cm accuracy horizontally and 2 cm accuracy vertically at 20 Hz frequency. Using two different receivers also the heading of the piling rig was retrieved. GPS data was read from the receiver in NMEA format via Ethernet connection. Typically when RTK GPS is used, the positioning accuracy is improved using one GPS receiver as a GPS base station and another GPS receiver as a GPS rover. The base station is installed to a known position and it provides correction signal to the GPS rover, that is installed to a work machine. In this case the

RTK GPS correction signal was received from VRS (virtual reference station) network via GPRS (General Packet Radio Service) modem. When VRS is used, there is no need for GPS base station in the worksite. Currently the VRS network covers almost entire Finland and the VRS service is also available in most of the European countries.

3.3. Sensors

The mechanism of the piling rig and installed sensors are presented in figure 6. The mechanism consists of three rotational joints and three prismatic joints. The values of these six joints should be measured in order to calculate the position of the TCP (Tool Center Point) according to the machine frame. When the position and orientation of the frame is measured using GPS positioning and inclination sensors, the vector from TCP to the GOAL position can be solved and based on this guidance to the machine operator can be provided.

Rotation *J0* is determined using two GPS receivers. Rotations *J2* and *J3* are measured using 2-axis tilt sensors in the frame and mast of the machine, because angle sensor could not be installed directly to the joints. Linear position sensors are needed for measuring joints *J1*, *J4* and *J5*. Expected operation conditions were harsh including temperatures from -20 to +30ºC and dust, grease, rain, snow, ice and vibrations. Accuracy requirements were within millimeter for linear position and 0.1 degrees for angle. The fact that all the sensors of the prototype should be installed outside of the actuators increased demands highly. In production version for example linear sensors could be installed inside hydraulic cylinders and very robust magnetostrictive sensors could be used.

To minimize the need for cabling sensors with CAN bus (Controller Area Network) interface were selected. CAN bus is a robust interface for control systems, sensor and actuators used in vehicles, work machines and industry. It offers 1 Mbps maximum data transfer rate. Most commercially available sensors use standard CANopen interface, which makes it very easy to implement systems with sensors from different manufactures. It also provides advanced features for configuration of sensors and diagnostics.

For tilt sensors there was really only one choice, robust packed MEMS sensors without any moving parts and with a CAN interface. For linear movements there were options from the laser based distance sensors to linear encoders using draw wire. For the distances from 0 to 4 m there are very few laser distance sensors that offer accuracy better than 5 mm and are suitable for outdoor applications, so draw wire sensors were selected. In joint J1 the draw wire sensor proved to be working unreliable, because the wire of the sensor broke easily. This sensor was replaced to a SICK DT-500 laser sensor. The chosen laser sensor provided distance measurement 5 times per second and ±3 mm accuracy. That was considered enough for the prototype but not for a production version.

For the sensors measuring the angle between the mast and the pile, there were two options: laser sensors or ultrasound sensors. Since the installation location of the sensor was very prone to get dirty, two ultrasound sensors were chosen. Since corresponding sensors were not found with CAN interface, the sensors were connected to the CAN bus via the analog-to-CAN converter.

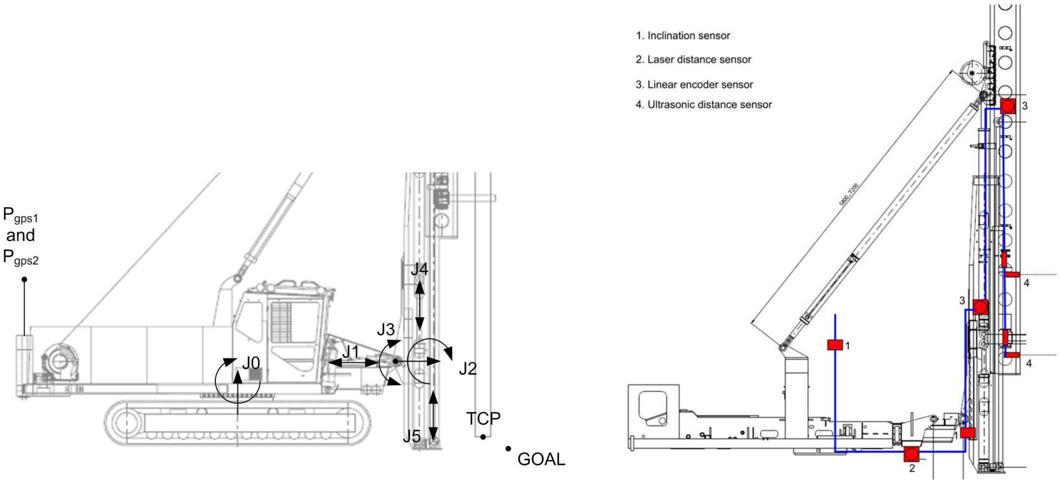

Figure 6. The joints of the piling rig and the sensors of the prototype system.

3.4. Software

The piling guidance software was implemented using PC computer, Windows XP operating system and C# .NET framework. The software was multi-threaded. There were different threads for RTK-GPS positioning, handling communication with CAN sensors and graphics. The positioning unit was connected by standard Ethernet techniques and received NMEA positioning data was parsed accordingly for the use of the other parts of the software. Position data was received 20 times per second. Also the status of the positioning system was provided to the operator of the machine. During the work it is important to ensure that the positioning device is working properly and the positioning accuracy is sufficient. The sensor reading was based on CANopen protocol and the sensor data was read 20 times per second from each sensor. The CAN thread also provides the status data from the sensors. This is useful for detecting malfunction of the sensors or CAN bus.

The graphics thread calculated and rendered the rig and mast positions and poses related to pile based on the data from the sensor and GPS threads. Graphics thread took care of all the operations related to updating graphics and interaction with the user. In figure 7 the user interface of piling guide software is presented. It helps the driver through the whole piling process from the pile selection and pile hammering to the storing of the pile realization data.

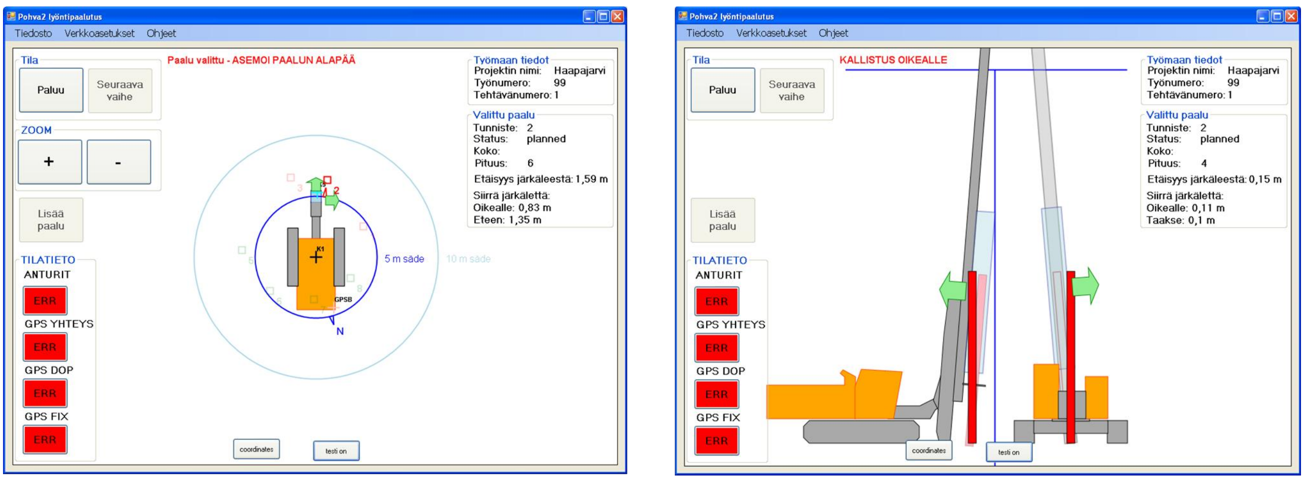

Figure 7. User interface of the piling guidance software and different phases of the guidance.

3.5. Wireless database connection

A log of a real time situation of all the work sites are maintained in the MySQL server. The information in the database contains detailed data of the worksite, designer, design software as well as individual pile data from the piling plant to the realization. The piling guidance software in the piling rig synchronizes the data between the local repository (XML file) and the database. This synchronization mechanism makes it possible for several rigs work in the same worksite simultaneously and all of them having all the time the newest possible information about progress of the worksite. The information exchange mechanism also makes it possible to store the realization data to the local repository during the connection blackouts and finally update the database when the network available.

The database and internet connection for the piling rig was implement using a mobile broadband network, that is based on Flash-OFDM technology and works at 450 Mhz frequency. In most European countries this frequency range is reserved for other purposes, so Flash-OFDM technology is used only in some European countries, e.g. Slovakia. Large cell size and relatively good performance makes it promising technique for data transfer from the moving work machines especially in the sparsely populated areas, where the coverage of the 3G telecommunication networks is limited. A theoretical maximum performance of the flash-OFDM technology is 2 Mbps and 20 ms for ping. A studied maximum speed down-link for average signal strength is about 750 kbps and for up-link about 450 kbps and ping for 256 bytes data packet is about 65 ms (Arjona et. al. 2008).

3.6. Web based real time piling map

In many cases in the worksite there is a need for a supervisor to be able to follow the progress of the work preferably in real time. Real time data can be useful e.g. in project management and logistics. In this project a web based tool for this purpose was developed. Anyone with password could follow the progress of the selected worksite pile by pile and also have summary of the situation in the site. From the piling data stored to a MySQL database a real time piling map is generated using SVG (Scalable Vector Graphics) technology. The piling map can be shown on a web browser and different colors can be used, for example green for finished piles (figure 8).

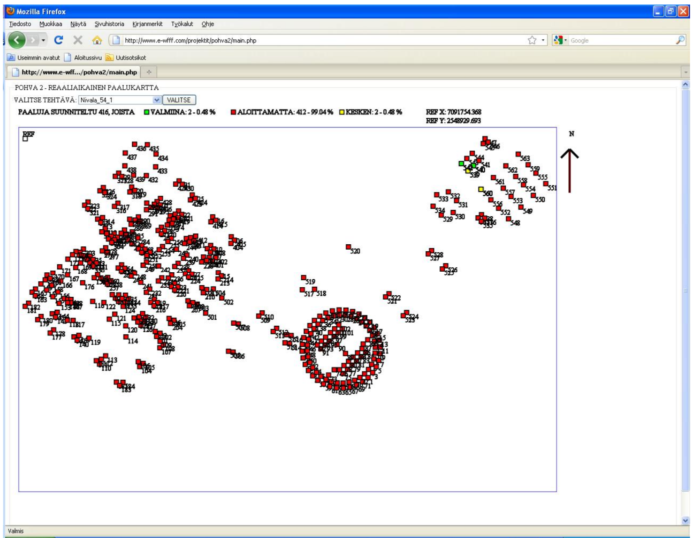

Figure 8. Web based real time piling map.

4. PROTOTYPE TESTS

The first test of the prototype system were carried out in winter 2009. First test results were encouraging and also pointing out that more study and tests should be made. The machine operators experienced the piling guidance software to be very helpful both in piling and documenting the piling work. Currently piling maps and piling documentation in the worksite are in paper format and the proposed system would remove the need for paper documents. The possibility of the data download through the database from the design software to the piling rig was highly valued. The fast design data update to the piling rig makes it possible to quickly respond for example to the changes in design.

The piling guidance tests have not been completed and more tests will be arranged in autumn 2010. In the preliminary tests 1 - 25 cm pile positioning errors were observed. These errors were mainly caused by inaccuracies in parameters, e.g. dimensions of the piling machine. During the calibration of the system the dimensions of the machine should be measured and zero positions of the sensors should be set carefully. The tests also pointed out that piling rig is a harsh and demanding environment for instrumentation. Temperatures between -20 and +30 ºC, high level of vibrations, snow and dust really tested the cabling and sensors mechanics.

During the tests the GPS system was functioning correctly except in the vicinity of high buildings, because building or other high structures can block the satellite signals. This can be a problem and reduce the usefulness of GPS positioning in this application. In figure 9 the functioning of the RTK GPS near high building is presented. When GPS quality value is 3, RTK GPS works properly. The DOP number is a value indicating the positioning accuracy. DOP value 1 is the ideal positioning accuracy and DOP values below 2 can be considered very good. As seen in figure 9, the quality value sometimes dropped during the tests and positioning data was inaccurate. During the work it is important to check periodically that positioning accuracy is sufficient.

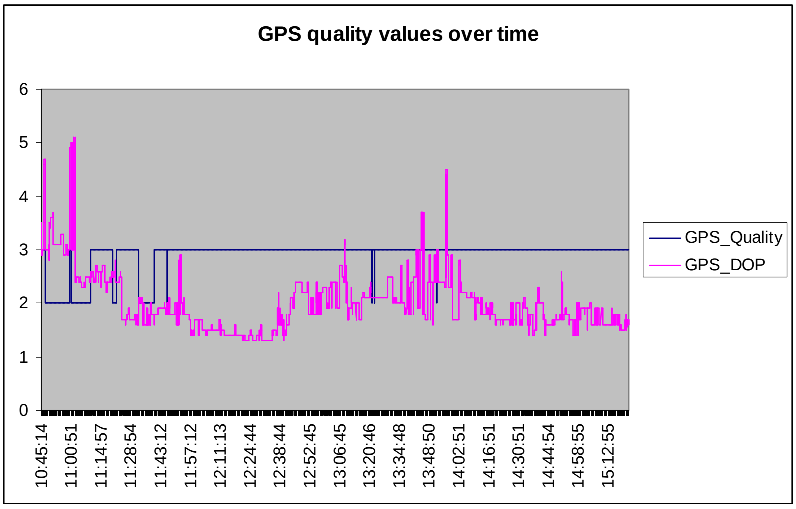

Figure 9. RTK GPS functioning near high buildings.

The performance of the mobile Flash-OFDM network proved to be appropriate for this kind of application. The nominal data rate were supposed to be 2 Mbps in both ways, but in practice the data rate was around 500 – 700 kbps downstream and 300 kbps upstream. The data rate was still enough also for the database updates for the pile maps with hundreds of piles. Ping remained in around 100 ms in every case.

5. CONCLUSIONS

The preliminary test results pointed out that the prototype system is highly potential, but the need for additional testing and study is clear. The prototype system is clearly improving the documentation and the follow-up of the process. The piling guidance systems helps the operator in the pile positioning and also keeping the mast of the piling rig aligned with the pile during hammering. Currently the assisting person helps the machine operator in these tasks. It should be carefully studied whether the total piling time could be reduced by using the guidance system. The biggest benefit is that when a piling guidance system is used, staking out operations are not needed in the worksite. The pile positioning accuracy should also be evaluated more vastly in further tests.

There were some minor problems during the tests concerning the sensors and in production version of the system protection of the sensors should be improved. The CAN bus with its diagnostic features proved to be very reliable and applicable to this purpose. The applicability of the GPS system near high obstacles like building or bridges should be further studied, because it can limit the usefulness of GPS positioning in this application. One important aspect related to GPS system is that GPS uses natively global WGS84 co-ordinate system. Piling is used for both building and infrastructure construction and various local or national co-ordinate systems are used in pile designs. Transformations between different co-ordinate systems are one potential source of errors when GPS positioning is used in machine guidance.

In this project one goal was to develop open data formats between CAD software and machine control systems. An XML based approach was selected and a format for digital piling plans was defined. Wireless data connection was very useful for transferring data between the work machine and the office. Same methods can be applied to other machines, e.g. deep stabilization machine. The designed prototype system is also quite general. It could be easily modified and applied for example to the deep stabilization process or some other processes needing machine guidance based on positioning and fluent two way information flow.

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